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1941

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and Petroleum

(INCORPORATED)

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1941

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FOREWORD

This is the second volume of TRANSACTIONS consisting wholly of papers on geology. The first was volume 115, published in 1935. Recent volumes devoted in considerable part to this field of the Institute were published in 1929, 1931, 1932 (*102*), and 1937 (*126*). Before the volumes of TRANSACTIONS were specialized, papers on geology appeared frequently.

By meetings, the period covered here is 1936–1941; but as these special volumes are compiled as soon as a sufficient number of TECHNICAL PUBLICATIONS has accumulated for a choice of contents, there is some slight overlapping with the last volume (*126*, 1937).

Four items in this volume—namely, the papers by Billingsley and Locke, McKinstry, and Wisser, respectively, and the symposium reporting Some Observations in Ore Search, deserve special mention. The first, cited by title, "Structure of Ore Deposits in the Continental Framework," was published separately by the Rand Fund in 1939. George M. Fowler organized the ore-search symposium and supervised it throughout to completion.

Besides the symposium, there are 19 papers. Many of them are on the geology of one district, mine, or deposit. Three, however, are on aerial photography and carry foreward from Volume 126 the proceedings of the Aviation Committee. With the present interest in aerial reconnaissance these papers may take on additional significance.

The chairmen of the Mining Geology Committee during the period of the volume were George M. Fowler, 1937; B. S. Butler, 1938; John M. Boutwell, 1939–40; Donald H. McLaughlin, 1941. Philip Krieger gave much valuable assistance at New York in organizing the respective annual meeting programs. W. E. D. Stokes, Jr., has been chairman of the Aviation Committee from 1937 to date.

To the chairmen of the respective committees, the 22 authors and the participants in the ore-search symposium the Institute is indebted for this volume.

A. B. PARSONS, *Secretary*.

NEW YORK, N. Y.,
August 4, 1941.

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CONTENTS

PAGE

Foreword. By A. B. Parsons 3

A.I.M.E. Officers and Directors 4

Committee on Mining Geology 7

PAPERS

Structure of Ore Districts in the Continental Framework. By Paul Billingsley and Augustus Locke. (With discussion) 9

Structural Control of Ore Deposition in Fissure Veins. By H. E. McKinstry. (T.P. 1267, with discussion) 65

The Environment of Ore Bodies. By Edward Wisser. (T.P. 1026, with discussion) 96

Some Observations in Ore Search. Symposium. (T.P. 1209) 111

Geology of the Getchell Mine. By Roy A. Hardy. (T.P. 1240) 147

Geology of the McIntyre Mine. By George B. Langford. (T.P. 903, with discussion) 151

Geology of the Gold Quartz Veins of Cornucopia. By G. E. Goodspeed. (T.P. 1035) 172

San Mauricio Mining Company, José Pañganiban, Camarines Norte, P. I. By H. L. Barr and D. L. Gardner. (T.P. 1187) 190

Carbon Dioxide Accumulations in Geologic Structures. By J. Charles Miller. (T.P. 841) 222

Factors of Composition and Porosity in Lead-zinc Replacements of Metamorphosed Limestone. By John S. Brown. (T.P. 1194). 250

Newly Recognized Features of Mineral Paragenesis at Leadville, Colorado. By Edward P. Chapman. (T.P. 1105) 264

Structure and Ore Deposition at Cartersville, Georgia. By Thomas L. Kesler. (T.P. 1226). 276

Barite Deposits of Northern Nevada. By Vincent P. Gianella. (T.P. 1200, with discussion). 294

Mercury Deposits of Huitzuco, Guerrero, Mexico. By C. W. Vaupell. (T.P. 842). 300

The Teziutlan Copper-zinc Deposit, Teziutlan, Puebla, Mexico. By A. W. Edelen and H. V. Lee. (T.P. 858) 314

Geological, Chemical and Physical Problems in the Marble Industry. By George W. Bain. (T.P. 1261). 324

Large-diameter Core Drill for Geologic Exploration. By Berlen C. Moneymaker and Portland P. Fox. (T.P. 1000, with discussion) 340

Use of Aerial Photographs in Geologic Mapping. By Wayne Loel. (T.P. 890, with discussion) 356

New Method of Mapping with Aid of Aerial Photographs and Slotted Templets. By W. H. Meyer, Jr. (T.P. 1081) 410

New Wide-angle Aerial-survey Camera. By A. W. Furbank. (T.P. 952) . . . 415

The Environment of Ore Bodies (discussion) 426

Index 429

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Structure of Ore Districts in the Continental Framework

By Paul Billingsley* and Augustus Locke,† Members A.I.M.E.

(New York Meetings, February, 1938, and February, 1939)

Certain adequately developed mining districts give complete three-dimensional patterns of ore bodies as clusters rising from roots in basement rocks with details controlled by structure of cover rocks. Examples are Goodsprings, Tintic, Bisbee, Leadville, Hedley, Eureka, Ely and Goldfield. In these and others the controlling structures in both basement and cover rock are elements of the neighboring regional structure and have been produced by rock movements in harmony with continental adjustments, which are usually steep tear faults in basement and thrust crumples in cover. Invariably the structures and movements in the districts have long geologic history and result from intersecting or superimposed deformations of different ages. Salt Lake districts show intersecting Uinta and Cordilleran elements; Colorado districts show intersecting pre-Cambrian and Tertiary elements, and Bisbee shows Tertiary superimposed on final Paleozoic folding. Thus the position of districts has been determined by the patterns of North American orogenic belts, which make crossroads in Rocky Mountains and blocks of superimposed deformation in Sierra Nevada, northwest Coast and Canadian Coast Ranges. Essential function of repeated deformation is to strengthen rock, as from shale to slate to schist to gneiss, and thus make it competent to carry channels to depth with or without addition of intrusives. The essence of a mining district is the presence of such competent rocks with long-lived, deep, penetrating breaks reopened to permit passage of heat and associated products from depths to surface. It is suggested that melts such as magmas; metamorphism up to and including granitization; alteration, such as orthoclase-quartz or quartz-sericite or garnet, and also mineralization, may all be by-products of such heat escape along channels made by tectonic forces at specific foci.

MAGNITUDES OF DISTRICTS (FIG. 1)

Any synthesis of ore deposits must deal with comparable units. Ore deposits are innumerable, but great ore deposits, commercially important for a generation or more, are few. The bulk of metals has come from districts of the first and second magnitudes (over $1,000,000,000 and over $250,000,000, respectively), and of these the United States and adjacent provinces of Canada and Mexico contain only 28, of which 9 are first magnitude: Butte, Coeur d'Alene, Bingham, Bisbee, Sierra Gold, in the West; Tri-State, Southeast Missouri, Michigan copper, Sudbury, in the East. Another 28 or 30 districts are of third magnitude (over $50,000,000).

This paper is published by the A.I.M.E. through the Charles F. Rand Foundation Fund. The manuscript was received at the office of the Institute on June 2, 1937, and a pamphlet was issued in February 1939.

* Consulting Mining Geologist, Still Waters, Burton, Washington.

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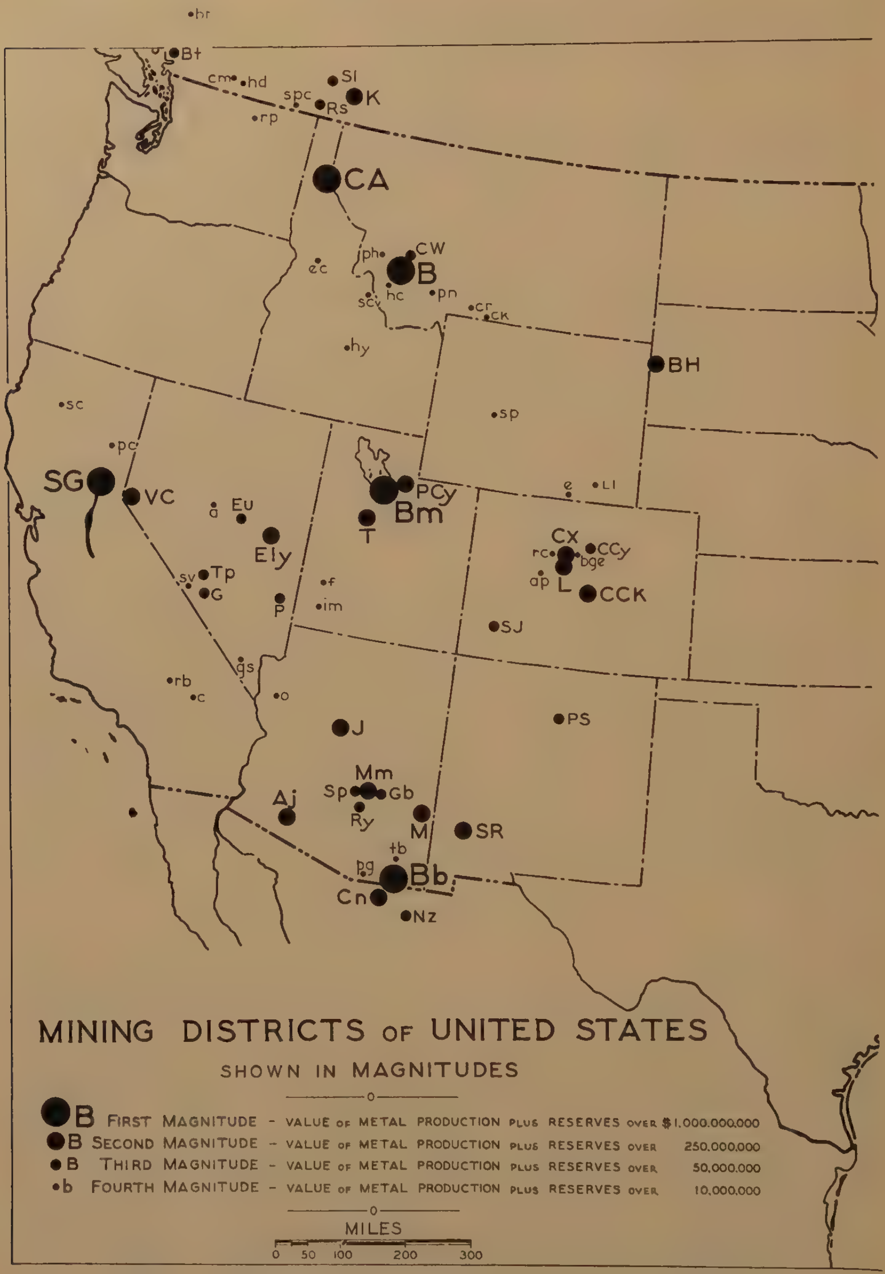
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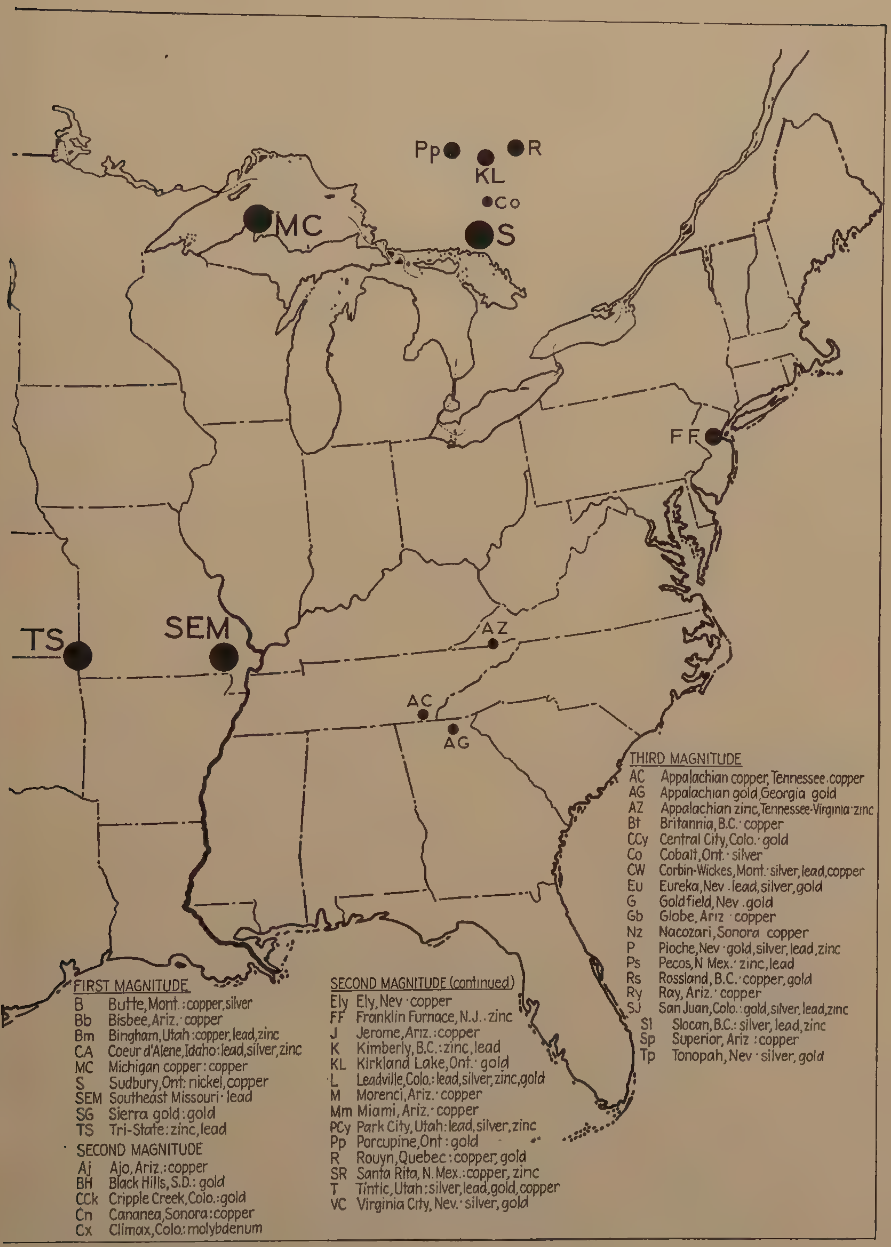
MINING DISTRICTS OF UNITED STATES
SHOWN IN MAGNITUDES
B FIRST MAGNITUDE - VALUE OF METAL PRODUCTION PLUS RESERVES OVER $1.000.000.000
B SECOND MAGNITUDE - VALUE OF METAL PRODUCTION PLUS RESERVES OVER 250.000.000
B THIRD MAGNITUDE - VALUE OF METAL PRODUCTION PLUS RESERVES OVER 50.000.000
b FOURTH MAGNITUDE - VALUE OF METAL PRODUCTION PLUS RESERVES OVER 10.000.000
MILES
0 50 100 200 300

FIG. 1.—MINING DISTRICTS OF UNITED STATES AND BORDERS.


Pp
R
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MC
S
FF
AZ
TS
SEM
AC
AG
FIRST MAGNITUDE
B Butte, Mont.: copper, silver
Bb Bisbee, Ariz.: copper
Bm Bingham, Utah: copper, lead, zinc
CA Coeur d'Alene, Idaho: lead, silver, zinc
MC Michigan copper: copper
S Sudbury, Ont: nickel, copper
SEM Southeast Missouri: lead
SG Sierra gold: gold
TS Tri-State: zinc, lead
SECOND MAGNITUDE
Aj Ajo, Ariz.: copper
BH Black Hills, S.D.: gold
CCk Cripple Creek, Colo.: gold
Cn Cananea, Sonora: copper
Cx Climax, Colo: molybdenum
SECOND MAGNITUDE (continued)
Ely Ely, Nev: copper
FF Franklin Furnace, N.J.: zinc
J Jerome, Ariz.: copper
K Kimberly, B.C.: zinc, lead
KL Kirkland Lake, Ont.: gold
L Leadville, Colo.: lead, silver, zinc, gold
M Morenci, Ariz.: copper
Mm Miami, Ariz.: copper
PCy Park City, Utah: lead, silver, zinc
Pp Porcupine, Ont: gold
R Rouyn, Quebec: copper, gold
SR Santa Rita, N. Mex.: copper, zinc
T Tintic, Utah: silver, lead, gold, copper
VC Virginia City, Nev.: silver, gold
THIRD MAGNITUDE
AC Appalachian copper, Tennessee copper
AG Appalachian gold, Georgia gold
AZ Appalachian zinc, Tennessee-Virginia zinc
Bt Britannia, B.C.: copper
CCy Central City, Colo.: gold
Co Cobalt, Ont.: silver
CW Corbin-Wickes, Mont.: silver, lead, copper
Eu Eureka, Nev: lead, silver, gold
G Goldfield, Nev: gold
Gb Globe, Ariz: copper
Nz Nacozari, Sonora: copper
P Pioche, Nev: gold, silver, lead, zinc
Ps Pecos, N Mex.: zinc, lead
Rs Rossland, B.C.: copper, gold
Ry Ray, Ariz.: copper
SJ San Juan, Colo.: gold, silver, lead, zinc
Sl Slocan, B.C.: silver, lead, zinc
Sp Superior, Ariz: copper
Tp Tonopah, Nev: silver, gold

FIG. 1.—(CONTINUED).

In seeking the laws of the occurrence of ore deposits, we are concerned, for the present, with the districts that show floods rather than trickles of the mineralizing materials. The following descriptions are therefore mainly of deposits of first and second magnitude. Smaller deposits are included only where particularly well-known and illustrative.

NATURE OF DISTRICT STRUCTURES

A mining district is a block, not an area. It is penetrated by shafts. Thus it is three-dimensional, and is hard to portray on the conventional geological plan map. Without special precautions such maps become actively misleading.

The depth of this three-dimensional block is unknown until the district is bottomed. Hence early geological studies are invariably incomplete, and are unduly influenced by the vagaries of shallow ore distribution and by the accident of erosion, which is the surface map.

During the past decade a number of ore deposits have been so definitely bottomed that their structures can be studied as complete units. Among these in the West may be listed:

Ely porphyry deposits
Bisbee porphyry deposits
Ajo porphyry deposits
Tintic ore funnels
Eureka ore funnels
Bisbee ore funnels
Cananca ore funnels
Hedlcy ore funnels
Leadville ore spreads
Park City ore spreads
Goodsprings ore spreads
Cripple Creek fingered ore funnels
Comstock fingered ore funnels
Goldfield fingered ore funnels
Coeur d'Alene vein ore shoots
Calico vein ore shoots

In certain places a bottom at no great additional depth is suggested by progressive changes, as:

Butte—east-west vein ore
Bingham—ore funnels in limestone
Central City—vein ore shoots
Michigan copper—ore shoots in fissures

At others there is as yet no sign of a bottom:

Butte—Northwest vein ore
Sierra gold—shear zone ore shoots in basement
Jerome—ore pipe in basement
Black Hills—ore pipe in basement
Michigan copper—ore shoots in steep tilted lava flows

At these last the magnitude of the block is greater than the extent of penetration by workings.

Some of the districts that are bottomed at least in part, and which illustrate complete district structures, are described in the following pages. As will be seen, the normal elements of district structures are:

1. Folds in sediments or bedded volcanics	make the channels
2. Thrust faults	
3. Tear faults	
4. Intrusive rocks	occupy the channels
5. Alteration funnels	
6. Ore networks	
7. Normal faults—impose subsequent modification	

Descriptions of Districts

1. Goodsprings, Nevada: sedimentary; intrusives few; folding intense.

2. Tintic, Utah: sedimentary; intrusives important; folding moderate.

3. Bisbee, Arizona: sedimentary; intrusives important; folding moderate.

4. Leadville, Colorado: sedimentary; intrusives abundant; folding slight.

5. Hedley, B. C.: sedimentary; intrusives abundant; folding moderate.

6. Eureka, Nevada: sedimentary; intrusives few; folding maximum.

7. Ely, Nevada: sedimentary; intrusives abundant; folding moderate.

8. Goldfield, Nevada: volcanic; intrusives important; folding moderate.

1. *Goodsprings* (*Figs.* 2 *and* 2*a*)

This fourth-magnitude district, producing zinc, lead, and gold, covers an area of 8 by 25 miles near the southern wedge of Nevada. The rather small individual mines are thus widely scattered.

The *sedimentary formations* include the thick Great Basin column from Cambrian to Jurassic, mostly limestones. In the northern part of the district they exhibit parallel northeasterly folds breaking like combers toward the eastward; they have gentle westerly dips, steep to overturned easterly dips, and are broken by successive thrust faults, on which slices of ground have been carried upward and eastward. In the south part of the district this pattern is almost obliterated by supervening structures. Most conspicuous are northwesterly steep straight faults with important horizontal displacement. Involved with these is an east-west sharp fold, which crosses the center of the district. The district has thus a *dual structure*, of which that found in the north extends on across into Utah, forming the Cordilleran thrust zone, and that found in the south extends northwest along the Nevada-California boundary as a broad zone of northwest "tear" faults separating Great Basin from Sierra Nevada trends. We call this zone the Walker line. Goodsprings is at the crossroads formed by the intersection of the Cordilleran thrust zone and the Walker line.

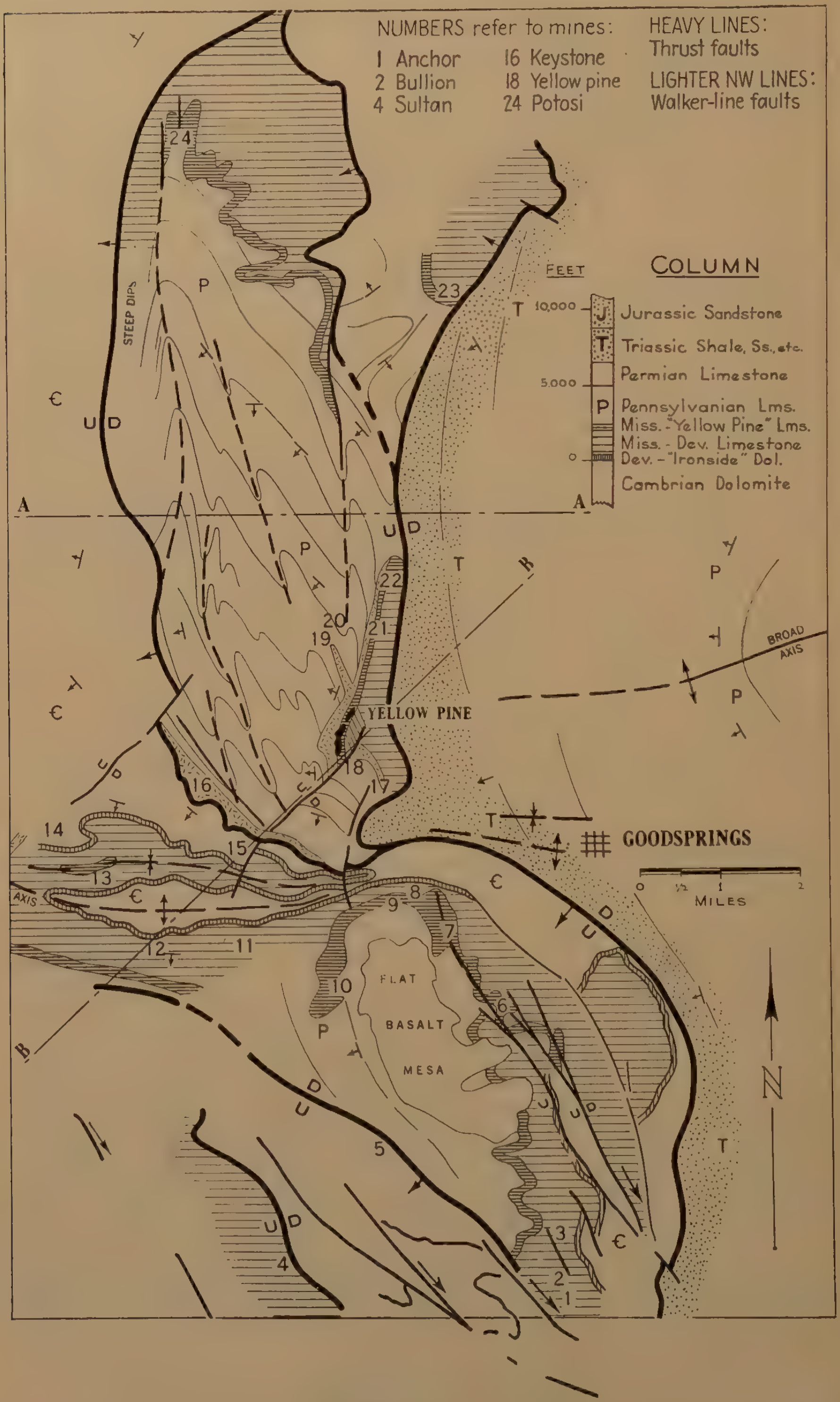


Fig. 2.—Goodsprings, Nevada—plan.

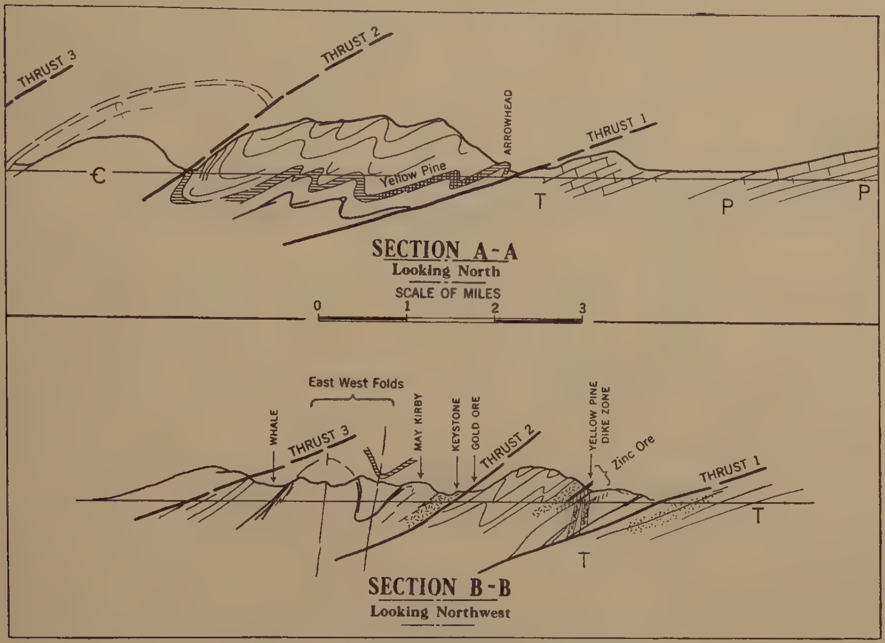


FIG. 2*a*.—GOODSPRINGS, NEVADA—SECTIONS.

Fig. 2 shows the Cordilleran thrust belt, which in the south part encounters and is broken up by the Walker northwest fault zone. At the junction is an east-west drag fold—complete syncline and anticline.

Porphyry dikes follow northwest faults (Yellow Pine) and feed spreads which follow the thrusts (Yellow Pine, Keystone). The larger ore bodies of zinc and gold are close to such dikes and spreads, but minor cool-temperature lead mineralization trails out for miles along the thrusts and along a pervious sandstone bed that overlies the Yellow Pine limestone. The Cordilleran folds and thrust slices are shown in section on Fig. 2*a*.

Intrusives are in scanty volume; monzonite porphyry dikes rise along certain of the northwest Walker faults, and spread as sheets on minor strands of the thrust faults. *Alteration*, mainly dolomitization, is focused in four places: northernmost Walker fault plus western thrusts (Potosi mine); main Walker zone plus eastern thrusts plus crossfold (Yellow Pine mine, gold mines, prospects); southeastward along main Walker zone (Anchor, Bullion mines, prospects); southern Walker fault plus western thrusts (Sultan mine).

The *Yellow Pine* mine is most completely developed. It exhibits in miniature the structures of the district. Its porphyry occurs in two northwest steep dikes, which expand above into a sheet blanketing the mine. A funnel of dolomitization encloses these, drawing in at depth toward a breccia pipe alongside the northern dike. The ore bodies occur as mantos within the alteration funnel, their position and attitude determined by minor thrust strands traversing favorable lower Missisippian limestone rich in fossils.

Sources of Information, Goodsprings

1925	P. Billingsley: Report on Potosi mine for International Smelting Co. Level maps, 1 to 600; surface map, 1 to 2400.
1926	P. Billingsley: Report on Yellow Pine mine for International Smelting Co. Level maps, 1 to 600; surface map of Yellow Pine area, 1 to 1200; reconnaissance surface map of district, 1 to 62,500.
1927–28	P. R. Murphy and F. Cameron: Report on Other Mines of District for International Smelting Co. Level maps, 1 to 600.
1931	D. F. Hewett: U. S. Geol. Survey *Prof. Paper* 162. Surface map of district, 1 to 62,500.

2. *Tintic* (*Figs.* 3 *and* 3*a*)

The Tintic district, southwest of Salt Lake City, is of second magnitude, producing silver, lead, gold, copper and zinc; its area is about 5 by 5 miles.

Its *sedimentary column* is of thick Great Basin type, from basal Cambrian quartzite to upper Mississippian, mostly limestones. These rocks are found in northeasterly folds, a syncline 4 miles wide to the west of a narrower anticline. The folds plunge northward; are overturned eastward; and contain minor sympathetic wrinkles. Overturned limbs and minor wrinkles pass generally into thrust faults of small displacement (Fig. 3*b*).

This system of northeasterly folds is cut by northwest steep faults, spaced about a mile apart, on which the south side is offset easterly. The predominant horizontal displacement marks them as tear faults. Along them and slightly later in age are sets of herringbone northeast fissures, which are their "tension crack" element. The *dual district structure* thus consists of the northeasterly fold-thrust system of the Cordilleran thrust zone, and a tear-fault system which is coincident with the south margin of the Uinta Mountain ancient high mass.

Intrusives are of three main groups, all later than the dominant structures. The earliest is monzonite, focused at the south spoon of the syncline, and appearing intermittently to the northward on thrust strands. Later is quartz porphyry, intruded at two centers and spreading on northeast tension fissures. Latest of all, barely antedating the ore itself, is "pebble dike" material, a sludge of quartz porphyry matrix and crushed quartzite containing rounded pebbles of all the deep rocks. This is close in position to the quartz porphyry dikes but extends on the northeast fissures farther from the intrusive centers.

Alteration consisting of dolomitization, silicification, pyritization, etc., occurs in funnels set around the district in a pattern obviously controlled by the wrinkles, thrusts, and tear faults. Pebble dikes form a skeleton web within the alteration masses, and in depth breccia pipes or porphyry prongs are found at their foci. *Ore bodies* form clusters which coalesce in depth to roots which are characteristically northeast tension fissures, situated at the intersections of northwest tear faults with northeasterly wrinkle thrust systems. These wrinkles are most strongly developed at shallow depth and in those parts of the stratigraphic column where strong and weak members are superimposed, such as quartzites, overlain by thin limestones and shales.

Thus along the southern tear fault, we find, at successive wrinkles, the Centennial Eureka, Grand Central, Mammoth, Iron Blossom, Sioux, and possibly Eureka Standard mines. Along the central tear fault are the Gemini, Bullion Beck, Chief Consolidated and Godiva mines. Along the northern tear fault are the North Lily, Eureka Lilly, and Tintic Standard mines.

The Centennial Eureka, Chief Consolidated and Tintic Standard mines are among the most perfect *complete ore clusters* known (Fig. 3*c*) with root fissures, breccia pipes or porphyry prongs, central ore mass and fingers of ore delicately controlled by tear faults, tension cracks and thrust strands, traversing variously favorable and hostile rock.

Fig. 3 shows the Tintic syncline, plunging northerly, outlined by Tintic quartzite and Ophir shale. The northern part of the syncline is buried under surface flows of Packard rhyolite. At the southern spoon end is the monzonite intrusion, which has an overhanging northern edge and which passes eastward into flows. It is slightly later than the rhyolite. The main fault and fissure pattern is also shown, while the orebodies, which do not outcrop, appear in horizontal projection. Their three-dimensional shape is indicated by the special examples on Fig. 3*c*.

Fig. 3*a* narrows the ore bodies down to their deep foci, or roots, and shows the position of these in respect to the main structural elements. The syncline, from west around to east, is subdivided into (*a*) steep western limb, (*b*) southwest steeply crumpled wedge, (*c*) block of gentle northward dips, and (*d*) block of westward dips with eastward thrusts. It is cut by the three tear faults, of which the southern (Sioux-Ajax-California) is developed mainly in blocks *b* and *c*; the central (Yankee-Chief-Gemini) in blocks *a* and *c* crossing the prow of wedge block *b*; and the northern (East Fissure) in block *d*. Ore foci are aligned along these faults at intersections with internal structures of the respective blocks. In blocks *a* and *b* these are crumples wherein the steep limb predominates (Centennial-Eureka, Chief Consolidated). In block *c* they are northeast fissures (Iron Blossom), and in block *d* they are thrust crumples wherein the flat limb predominates (Tintic Standard, North Lily). Fig. 3*b* shows these features in cross section.

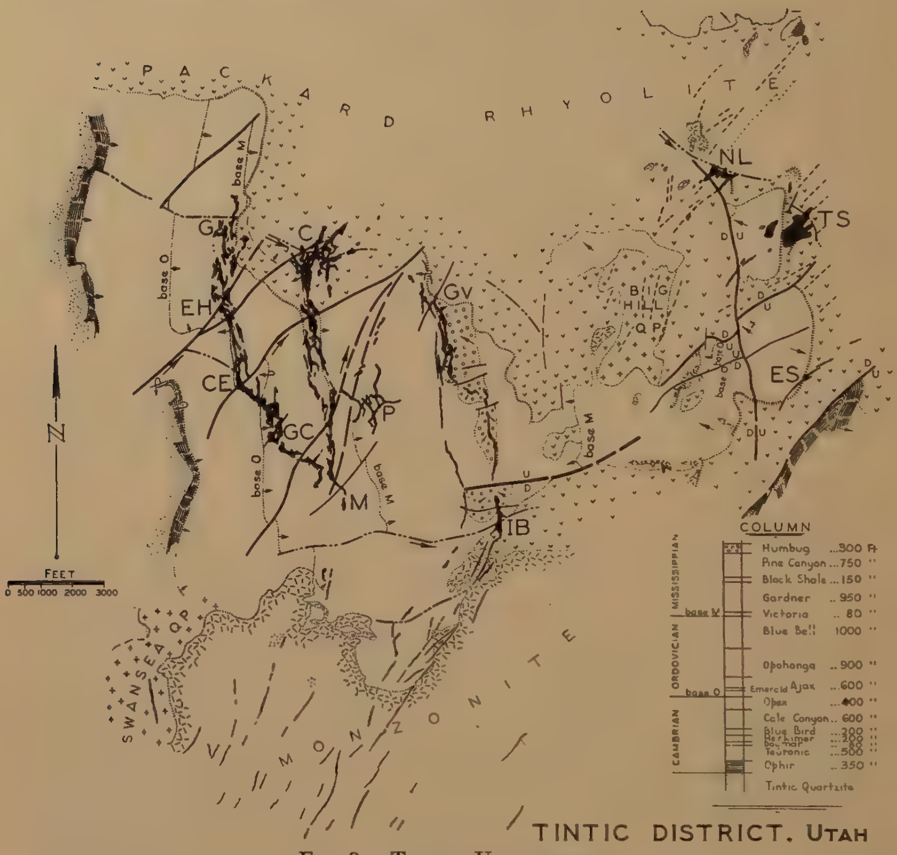


FIG. 3.—TINTIC, UTAH—PLAN.

Dot and dash lines, tear faults. Solid heavy lines, other faults. Hatched lines, thrust faults, bringing limestone against rhyolite. Dash lines (in eastern part), pebble dikes.

Ore Foci	Company	Yield	Ore Foci	Company	Yield
C	Chief Consolidated	$60,000,000	*IB*	Iron Blossom	$27,000,000
CE	Centennial Eureka	55,000,000	*M*	Mammoth	30,000,000
EH	Eureka Hill—Beck	25,000,000	*NL*	North Lily	7,000,000
ES	Eureka Standard	7,000,000	*P*	Plutus	5,000,000
G	Gemini	[a]	*TS*	Tintic Standard	75,000,000[c]
GC	Grand Central	[b]		Veins in porphyry	10,000,000
GV	Godiva	16,000,000			

Base M.......................... Base of Mississippian (Victoria)
Base O.......................... Base of Ordovician (Ajax)

[a] Included in Eureka Hill.

[b] Part included in Centennial Eureka, part in Mammoth.

[c] Yield plus reserve.

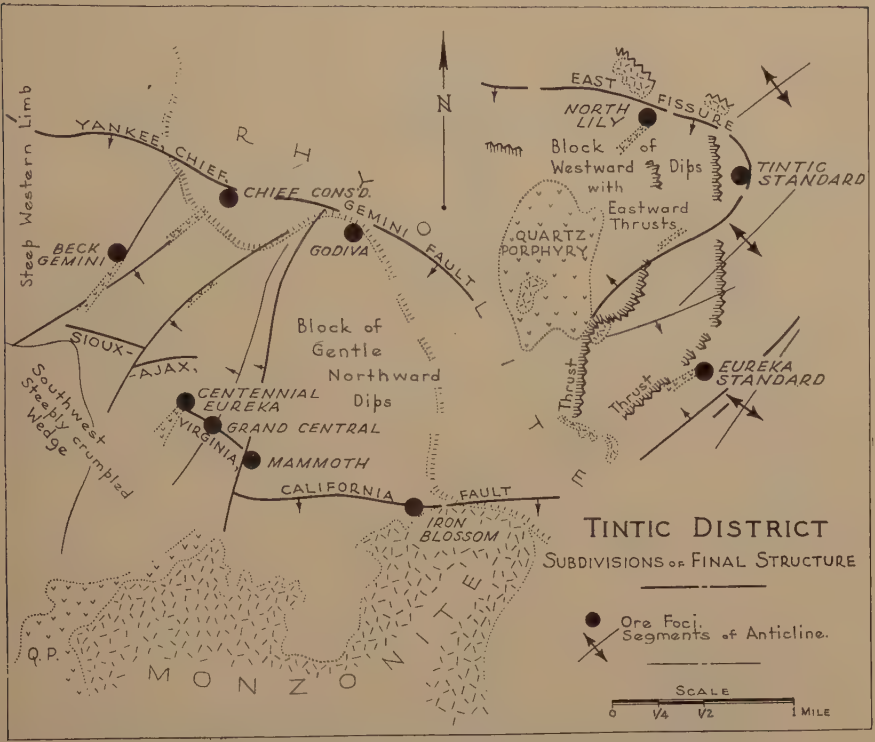


FIG. 3a.—TINTIC, UTAH—SUBDIVISIONS OF STRUCTURE.

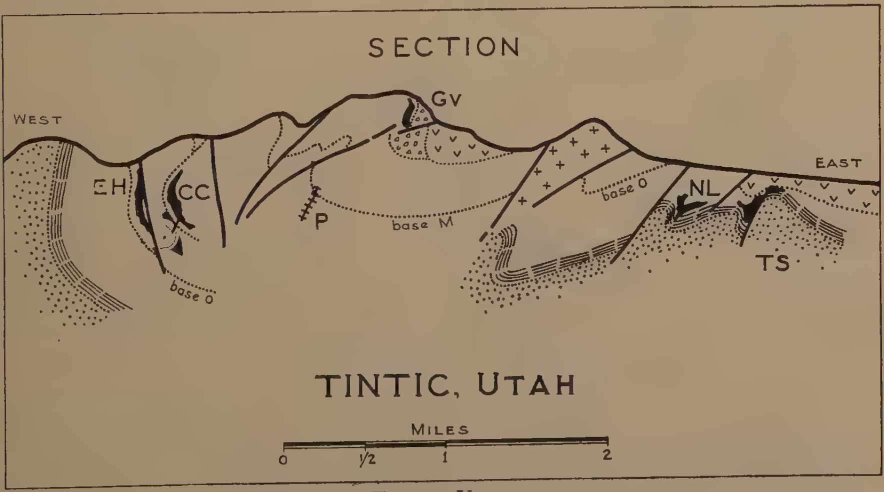


FIG. 3b.—TINTIC, UTAH—SECTION.

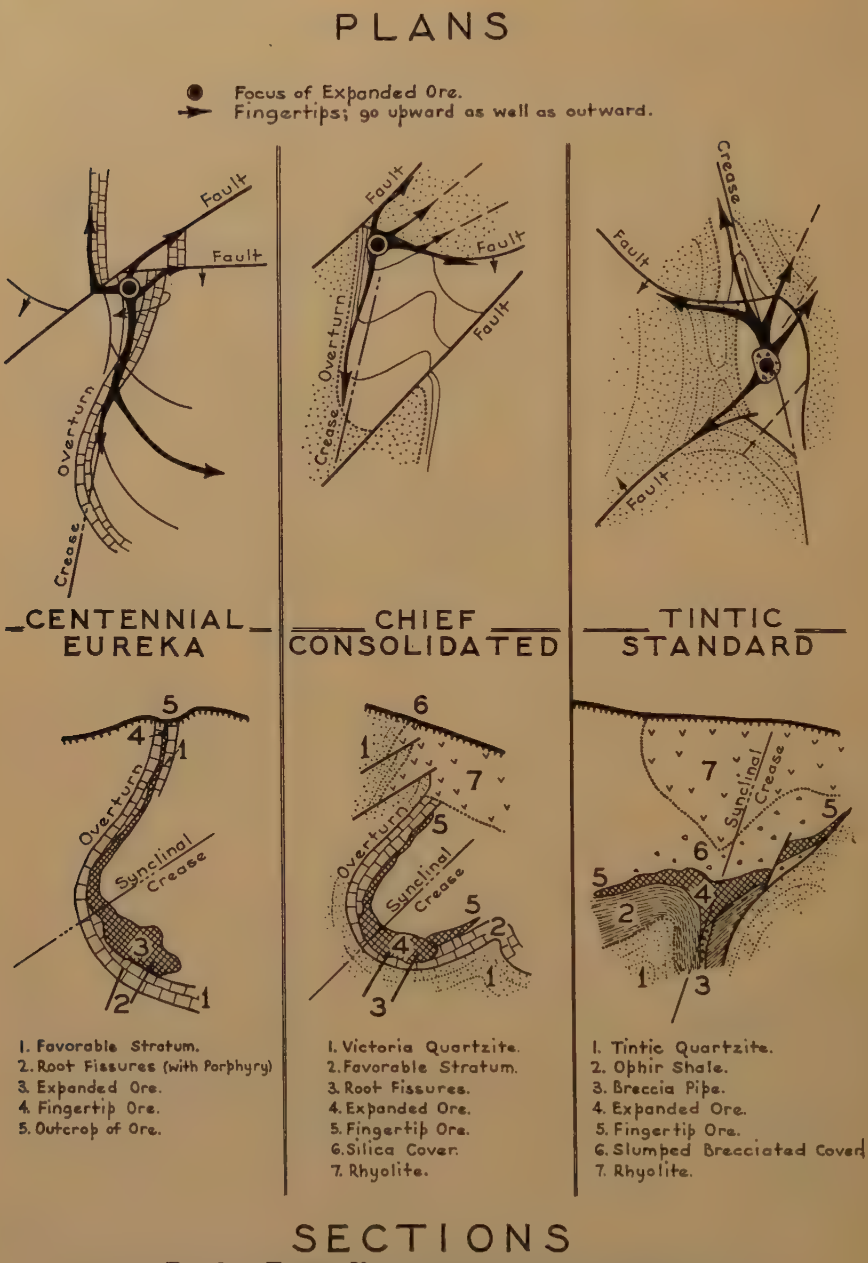


FIG. 3c.—TINTIC, UTAH—DIAGRAMS OF ORE CENTERS.
Reprinted from Ore Deposits of the Western States (Lindgren Volume).
A.I.M.E., 1933.

Sources of Information, Tintic

1898 G. W. Tower and G. O. Smith: Geology and Mining Industry of Tintic District. U. S. Geol. Survey 19th Ann. Rept.

1915 W. Lindgren: Processes of Mineralization in the Tintic Mining District. *Econ. Geol.* (1915) **10**, 225.

1917 G. W. Crane: Geology of Ore Deposits of Tintic Mining District. *Trans.* A.I.M.E. (1917) **54**, 342–355. Maps of Chief Consolidated mines, 1 to 600.

1919 W. Lindgren and G. F. Loughlin: U. S. Geol. Survey *Prof. Paper* 107. Surface maps, 1 to 9600 and 1 to 62,500.

1920–36 P. Billingsley: Repts. to International Smelting Co., Tintic Standard Mining Co. and Chief Consolidated Mining Co. Maps of all East Tintic mines, 1 to 480 and 1 to 240, and many other mines, 1 to 600; surface maps of district, 1 to 1200.

1927 P. Billingsley: North Lily Development in East Tintic. Abst. in *Min. and Met.* (April 1927) **8**, 182.

1932 P. Billingsley: Utilization of Geology in Tintic. Ore Deposits of the Western States (Lindgren Volume), 716–722. A.I.M.E., 1933.

1933 P. Billingsley: Tintic District. *Guidebook* 17, Int. Geol. Congress.

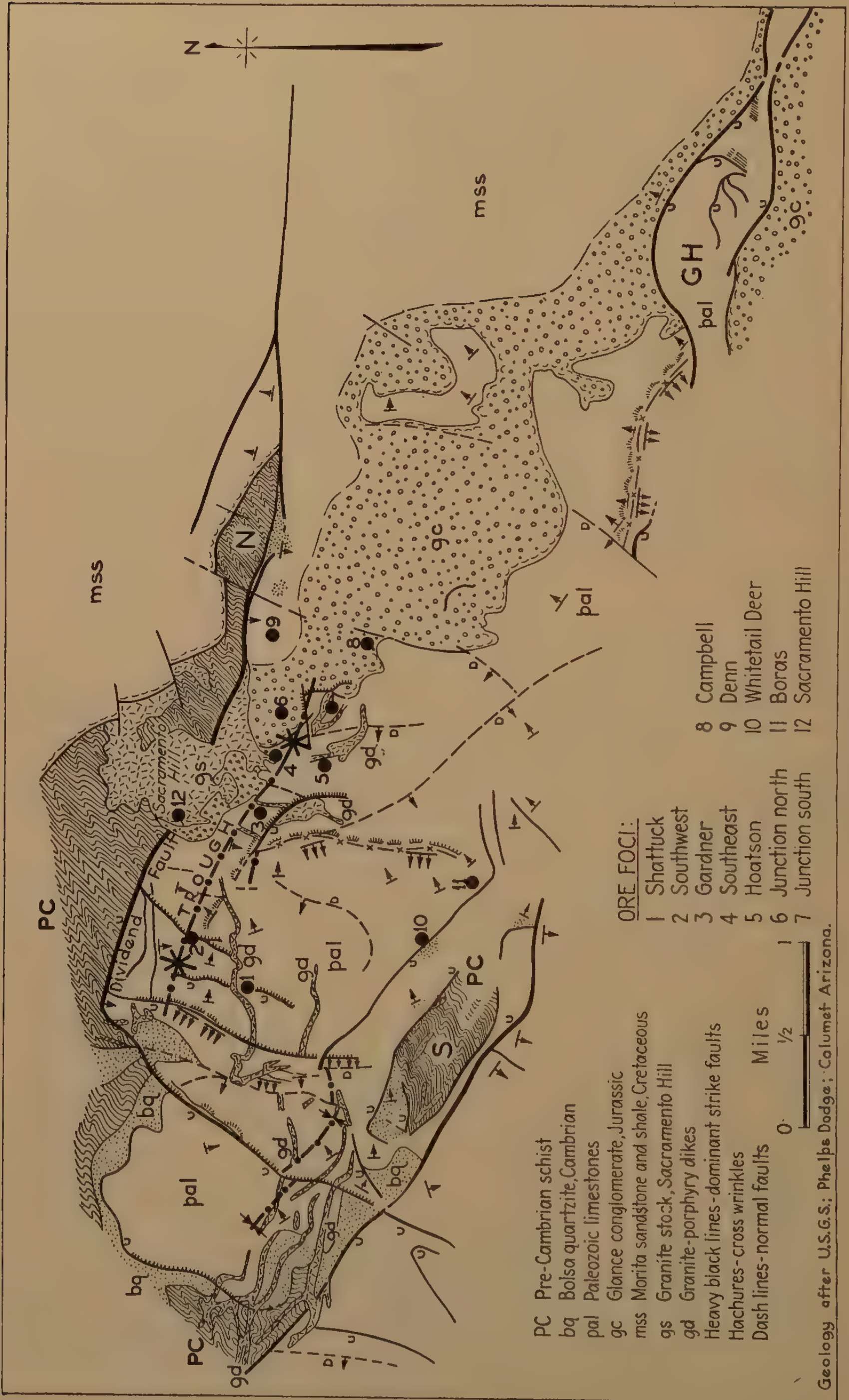
3. *Bisbee* (*Fig.* 4)

This is a district of the first magnitude, producing copper. Its area is about 2 by 5 miles, lying in southeastern Arizona a few miles north of the Mexican boundary.

Its *sedimentary column* is of continental shelf type, consisting of thin Paleozoic limestones up to the lower Pennsylvanian, overlain unconformably by Mesozoic conglomerate and shale. The basement is of pre-Cambrian schist.

The Paleozoics lie in a northwesterly syncline 2 miles broad, bounded by sharp anticlines. The system plunges toward the east. The folding, largely pre-Mesozoic, was sharpened: (1) in Jurassic time producing the erosional dump of Glance conglomerate, and (2) in post-Cretaceous time, for the shales are on end and overthrust along the marginal anticlines. The axis of the syncline crowds against the northern rejuvenated anticline with strong strike faulting, which accentuates it into a trough. Steep northwest faults are emphatic also on the south anticline, and are the major second structural elements of the district. Cross fissures and cross wrinkles in the syncline are a third element, extending like the teeth of a comb southward from the axis across the gentle south limb.

The multiplicity of the Bisbee structure is found in the sharpening of post-Pennsylvanian folding by Mesozoic and post-Mesozoic folding, thrusting and faulting, all essentially superimposed. The early folds are part of a Final Paleozoic mountain arc, which traverses southern New Mexico and Arizona; the later sharpenings are phases of Early Creta-



Geology after U.S.G.S.; Phelps Dodge; Calumet Arizona.

FIG. 4.—BISBEE, ARIZONA.

ceous (Nevadan) and Early Tertiary (Laramide, etc.) orogeny. The steep northwest faults suggest tears of Walker line type.

Intrusives, of at least three groups, rise along the broken north limb of the synclinal axis, and spread either as mushrooms above the basement to the north or as widespread sheets along flat planes of displacement that shear the Paleozoic formations in the syncline to the south. These intrusions are:

1. The granite porphyry neck and mushrooms of Sacramento Hill (pre-Mesozoic).
2. Contact breccias enveloping the south side of the neck and filling the synclinal trough near by; also spreading on flat shears (pre-Mesozoic).
3. Granite porphyry dikes and sheets, cutting contact breccias, rising on north-south cross fissures and spreading on flat shears (probably post-Mesozoic).

Alteration, mainly silicification, fills the synclinal trough and seeps out along the comb-teeth made by the cross fissures and wrinkles. Masses of pyrite somewhat less widespread and somewhat skeletonized, may be regarded either as a final stage of alteration or as the initial stage of ore deposition.

Ore bodies occur in clusters, gathering together downward into roots in the synclinal trough, at specific positions controlled by the intersections of cross fissures. Great spreads of ore form a band of stopes around the south margin of Sacramento Hill porphyry and breccia, with fingers extending southward along the comb-teeth fissures. The principal clusters are, from west to east:

1. Southwest, Shattuck.
2. Copper Queen-Gardner, Lowell, Sacramento, Oliver.
3. Porphyry ore bodies, Junction, Briggs.
4. Denn, Campbell.

The *ore-cluster form* is excellently developed in the Southwest, Shattuck, Gardner and Campbell mines. The gathering in downward of disseminated "porphyry" copper ore into roots, and the penetration of such roots below porphyry into underlying formations, is well illustrated in the Northeast Sacramento Hill ore body.

Fig. 4 shows a syncline with northwest and southeast axis, plunging gently southeast. The trough of the syncline is crowded against the north limb and is accentuated by faulting. On both sides of the syncline are ridges of basal beds, which are also accentuated by faulting along their borders. These folds and ridges are Final Paleozoic structures rejuvenated since the Cretaceous.

The floor of the syncline is crossed at intervals by transverse wrinkles and faults that often produce strips of westward dips contrary to the normal plunge of the floor (see lines of arrows). Not shown, but equally important, are flat shears almost parallel to the bedding, on which have spread sheets of porphyry and silica. Porphyry, contact breccia (seen on the south edge of Sacramento Hill), silica and ore have risen from roots in the trough and have spread across the synclinal floor under the control of transverse structures and flat shears.

Sources of Information, Bisbee

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1909 J. M. Boutwell: Unpublished study, Copper Queen area.

1909–30 Geological Staffs. Level maps Phelps Dodge mines, 1 to 1200; Calumet and Arizona mines, 1 to 600.

1916 Y. S. Bonillas, J. B. Tenney and L. Feuchère: Geology of Warren Mining District. *Trans.* A.I.M.E. (1916) **55**, 284.

1917 P. Billingsley: Mapping of Calumet and Arizona mines; 1 to 600; cross section set, 1 to 1200.

1923–26 R. Blanchard in collaboration with A. Locke: Mapping of Phelps Dodge mines, surface 1 to 24,000; Gardner and Lowell mines, 1 to 1200 and 1 to 600.

1924–25 H. M. Kingsbury in collaboration with A. Locke: Mapping of Phelps Dodge mines: Southwest, Uncle Sam and Shattuck mines, 1 to 1200 and 1 to 600.

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1927 E. H. Wisser: Oxidation Subsidence in Bisbee. *Econ. Geol.* (1927) **22**.

1931 H. A. Schmitt: Surface Studies of post-Cretaceous Thrusting. Unpublished report to A. Locke.

1933 J. B. Tenney: Int. Geol. Congress *Guidebook* 14 (1933). Compendium.

4. *Leadville*—(*Fig.* 5)

The Leadville district, of the second magnitude, produces lead, zinc, silver and gold. It occupies an area of 3 by 4 miles near the Continental Divide in north central Colorado.

The *sedimentary column* is of the Continental shelf type; thin Paleozoics to the Mississippian, overlain, with a break, by thick upper Pennsylvanian clastics and shales. The basement is of pre-Cambrian granite and schist.

The basement of this region is characterized by steep northeast to north structure formed by elements of the late pre-Cambrian orogeny. The later rocks are nearly flat, except along sharp zones of Tertiary thrust faulting. Such a zone delimits the western edge of the ancient high masses of the Colorado Front Range. This thrust zone, north-south in direction, crosses the eastern edge of the Leadville region and minor strands traverse the district itself. The basement structures were also locally rejuvenated in Tertiary time along northeasterly shear zones.

Leadville has thus the *superimposed elements* of northeasterly pre-Cambrian structure and its Tertiary rejuvenation, and further the *intersecting* crossroads made by these and the north-south Tertiary thrusts.

Intrusives are present to the extent of one-half the mass of rock above the basement. They rise through this in dikes along the northeast zone and also form a granite porphyry stock or neck at Breece Hill, which lies at the major crossroad of the district. From the top of the Breece Hill stock porphyry obliterates all sediments for a mile around (Fig. 5*a*), forming a mushroom that is emphasized by a ring of faults. Farther out it frays to thin sheets and intervening slices of Paleozoic limestones appear. The porphyry sheets continue for many miles, being particularly persistent along the unconformity at the base of the Pennsylvanian clastics.

Ore bodies occur in three clusters; one on the northeast belt at the intersection with a thrust east of the porphyry-fault circle; one on the belt at the intersection with a thrust west of the circle; and one farther northwest along this latter thrust. The ore bodies of the eastern cluster are in part mantos, which turn down to northeast fissure veins and breccia pipes (Ibex mine). Those of the western clusters are predominantly mantos, usually close under or over a porphyry sheet; and they gather down to inlets on elements of the western thrust zone, often marked by prongs of basal quartzite (Downtown mines).

The map and section in Figs. 5 and 5*a* show mild structures in nearly flat cover rocks resting on metamorphic basement. The basement structures, not shown, are northeasterly and are most extreme along a fissure-dike zone running through Breece Hill, marked by the gold stopes *G* at the northeast and by the stopes and faults at the southwest.

The basement is also sliced by two northwesterly thrust faults (Colorado Prince and Tucson Maid), and a center of porphyry intrusion has developed on the northeast fissure zone between these thrusts. The center is at Breece Hill, a porphyry mushroom one mile in diameter. From this, sheets spread out controlled by bedding-plane slips and by such stratigraphic planes as the top of the basement and the basal Pennsylvanian unconformity. Orebodies rise from roots on the thrusts and spread on similar bedded channels.

Sources of Information, Leadville

1886 S. F. Emmons: U. S. Geol. Survey *Monograph* 12. Compendium.

1907 S. F. Emmons, and J. D. Irving: U. S. Geol. Survey *Bull.* 320. Compendium.

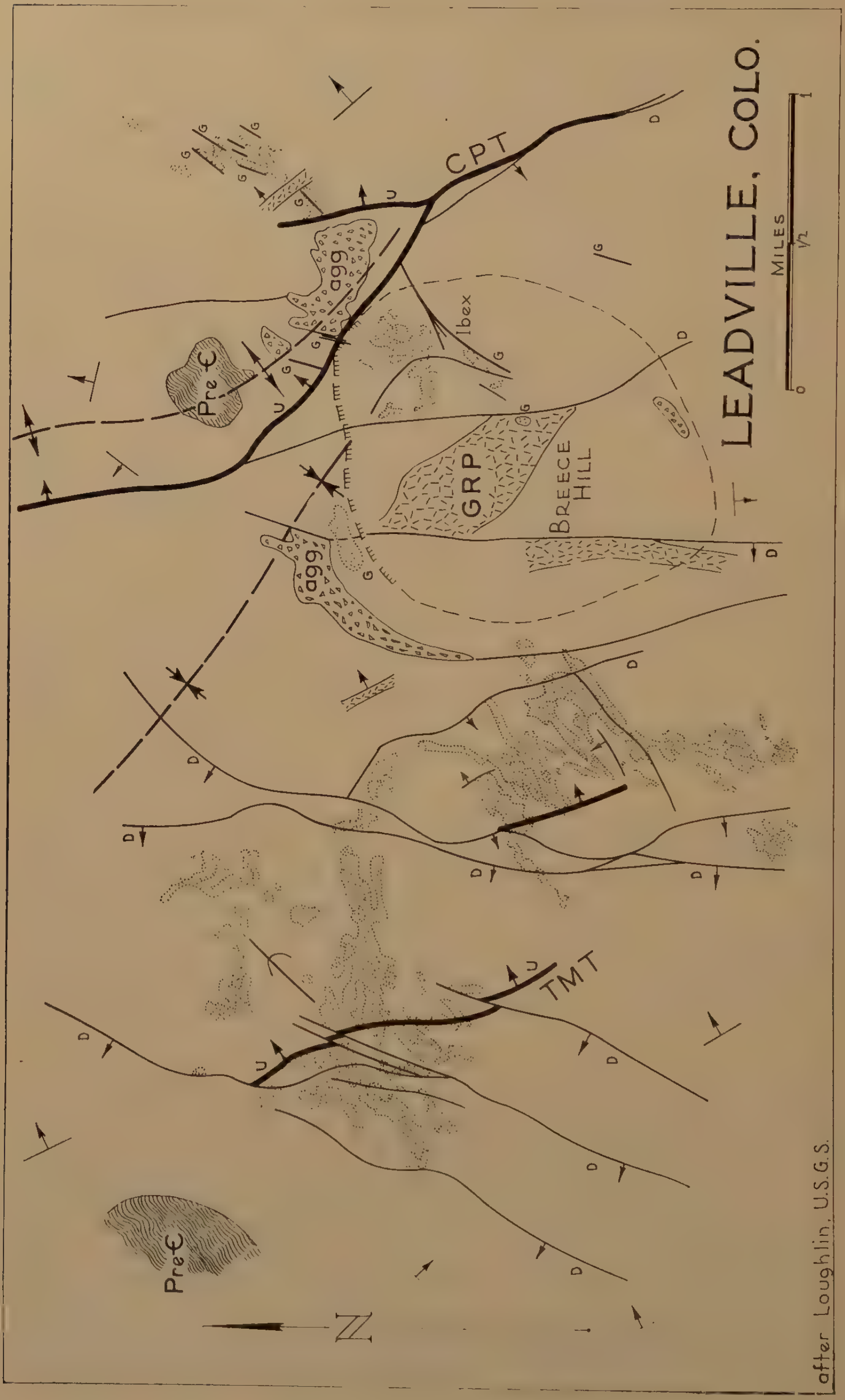
1918 G. L. Loughlin: U. S. Geol. Survey *Bull.* 681. Zinc carbonate ores.

1927 G. L. Loughlin, with Emmons and Irving: U. S. Geol. Survey *Prof. Paper* 148. Fine compilation, revision and interpretation, aided by mine maps of F. A. Aicher; surface and mine maps and sections, 1 to 48,000 and 1 to 9600.

1929 C. H. Behre: Structure and Stratigraphy near Leadville. Colorado Sci. Soc., 12.

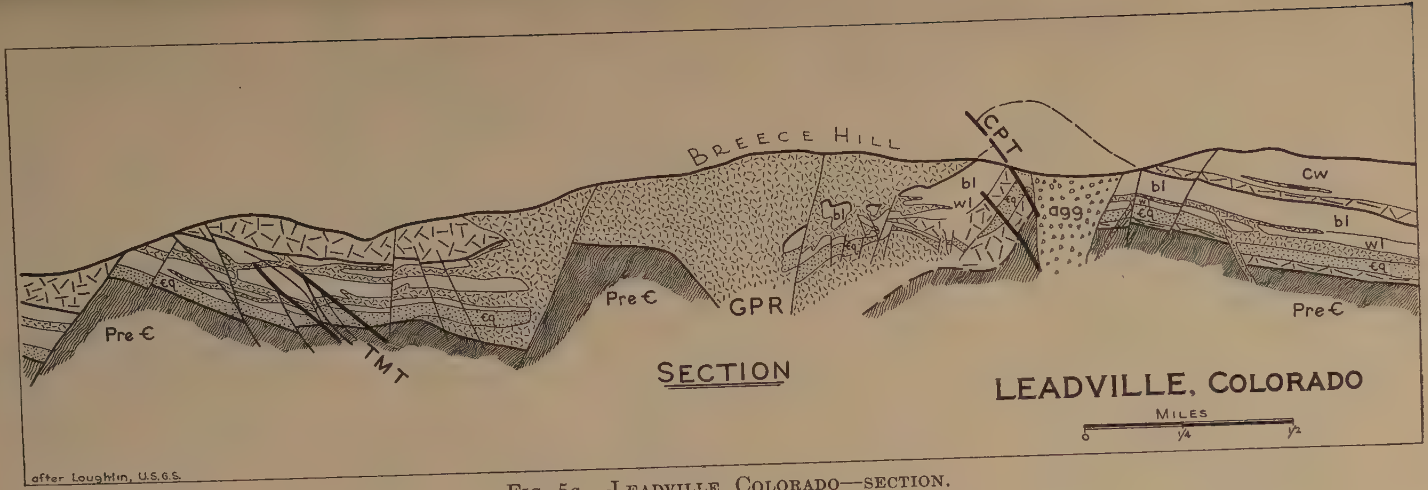
1930 Q. A. Singewald and B. S. Butler: Alma District (East of Leadville). Colorado Sci. Soc., 12, 13. Surface map, 1 to 36,000.

1923–30 A. Locke and P Billingsley: Various visits and study of engineers' reports.



after Loughlin, U.S.G.S.

FIG. 5.—LEADVILLE, COLORADO—PLAN.



after Loughlin, U.S.G.S.

FIG. 5*a*.—LEADVILLE, COLORADO—SECTION.

PC, pre-Cambrian basement.
€q, Cambrian quartzite.
Wl, White limestone.
CW, Weber grits.
Fine hachure, gray porphyry, on section only.
GPR, gray porphyry roots.
Circle of hachures, boundary of area in which gray porphyry obliterates Paleozoic formations.
Coarse hachure, white porphyry, on section only.
agg, rhyolite agglomerate.
Heavy lines, thrust faults.
CPT, Colorado Prince thrust.
TMT, Tucson Maid thrust.
Irregular dotted areas, stopes. Not shown on section, Fig. 5*a*, but would lie on limestones adjacent to gray porphyry sheets.

5. *Hedley* (*Fig.* 6)

The Hedley district, of fourth magnitude, producing gold from arsenical ores, is about one mile square. It lies on the eastern edge of the Coast Ranges in southern British Columbia.

Fig. 6 shows a "book" of thrust plates crossing a pile of west-dipping Mesozoic lime argillites, which carry also northwesterly crumples.

In addition to the main thrust planes as shown, the entire pile is marked by minor shearing almost parallel to bedding, and on such shears sill-like diorite intrusions have entered to the amount of 30 per cent of the total thickness. These are not shown. The argillites between these diorite sills contain the ore bodies, which likewise show control by shear strands and which are localized on the intersections of such strands with the northwesterly crumples.

The *stratigraphic column* of the region includes a metamorphosed Paleozoic basement complex, overlain unconformably by Mesozoic argillites and volcanics. The Mesozoics are tilted and locally closely folded and overthrust. Regional folds are on northwesterly axes sliced by strike faults. This is the structure of the composite orogenies of the north coast ranges. At Hedley an exceptional thrust zone runs transversely, with northeast strike. It is a book of "thrust" leaves, flat to steep, bunching together in depth, all dipping northwesterly. (See section on Fig. 6.) The beds of the intervening slices of rock also dip northwesterly in general, but show minor wrinkles running down the dip with associated axial faulting. These wrinkles of regional northwest strike, intersected by the northeast thrust book are the essential *dual elements* of the district.

The *intrusive sequence* is complex. In the position of a lowest thrust slice lies granodiorite, thick near the thrust book, fraying out toward the southeast. From its back rise dikes with the northwest course of the wrinkles. The higher thrust slices are intruded by hornblende-diorite, also thickest near the main thrust, also fraying out into sheets, and also springing upward into northwest dikes. The highest slice, however, is intruded by a more specialized rock, an augite-gabbro, mainly massed as a chonolith near the main thrust, but in addition exhibiting a few thin

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Formations:
  Contoured, argillites.
  lms, limestone.
  Si, silicified argillite.
Thrust Faults (heavy lines):
  B, Bradshaw.
  W, Windfall.
  Clx, Climax Breccia.
G, garnetized argillite.
AG, augite gabbro.
Gd, granodiorite.
Mines:
  1, Nickel Plate.
  2, Sunnyside.
  3, Bulldog.
  4, Kingston.
xxxx, Limit of alteration funnel.

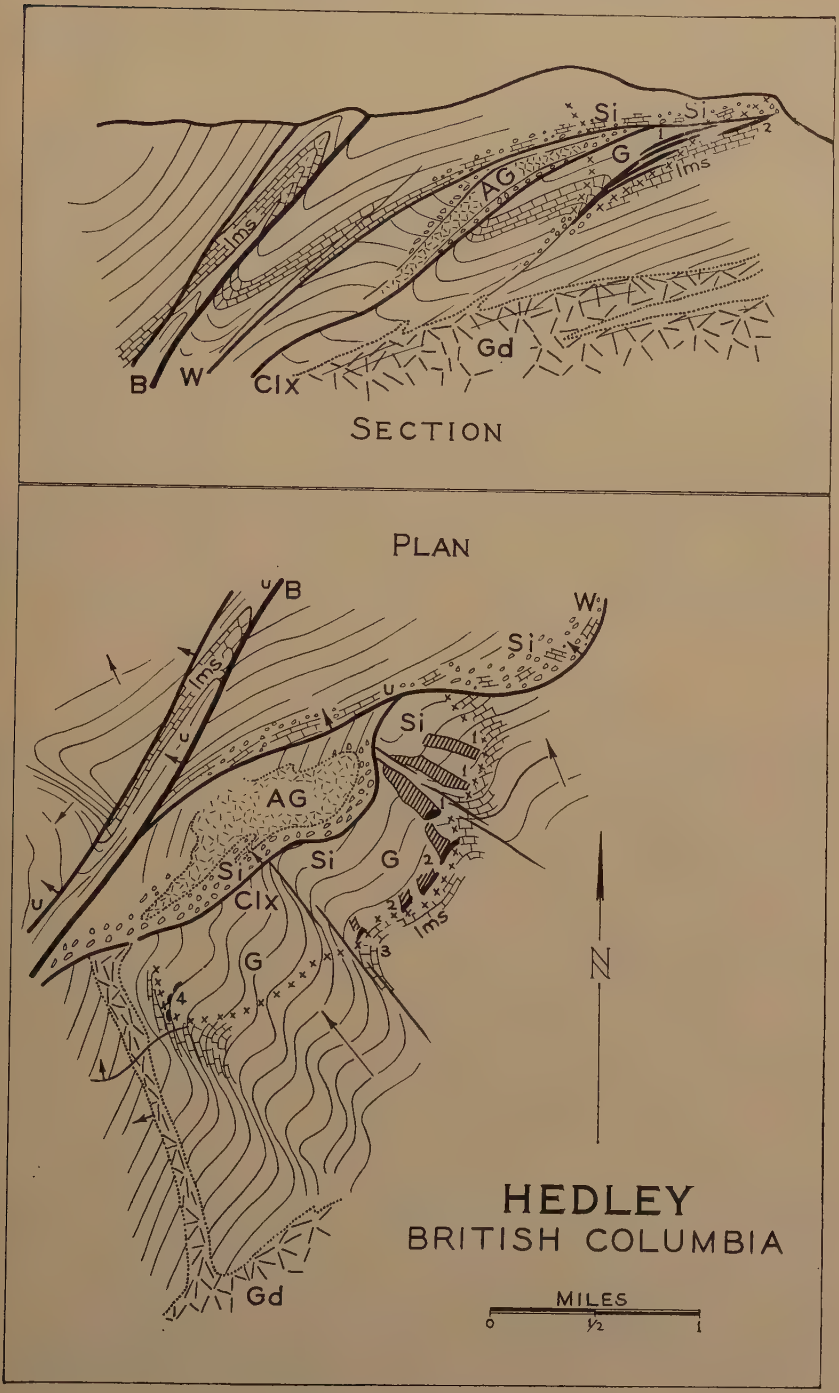

FIG. 6.—HEDLEY, B. C.—PLAN AND SECTION.
Legend on opposite page.

sheets, which angle acutely up through the bedding to the southeast. The order of intrusion of these rocks is: (1) hornblende-diorite, (2) augite-gabbro, (3) granodiorite.

Alteration is profound in a funnel a mile in diameter occupying the upper thrust slices. It is peripheral to the augite-gabbro chonolith and is characterized by abundant secondary augite, as well as the commoner garnet, epidote and carbonate. The upper part of the alteration funnel adjacent to the chonolith is a mass of complex breccia cemented by garnet and silica.

The *ore bodies* are bedded mantos, found raking northwesterly along the minor wrinkles. The principal ore-bearing wrinkle coincides closely with the northern margin of the alteration funnel, and its ore bodies (Nickel Plate), which are in overlapping layers, are invariably limited to the northward by the "marble line" marking the outer edge of the more intense alteration. A second wrinkle follows the southern margin of the funnel and the ore that has been found here (Bulldog) similarly dies out southward against marble. Between the two the alteration funnel has a flattish floor on which rest other ore bodies (Sunnyside). The Nickel Plate ore bodies are fully developed down to roots springing from a breccia pipe beneath the overhang of the gabbro chonolith.

Sources of Information, Hedley

1908 C. Camsell: Canadian Geol. Survey *Memoir* 2. Compendium. Surface map, 1 to 12,000.
1927 P. Billingsley: Report to Hedley Gold Mining Co. Surface map, 1 to 1200; level maps and sections, 1 to 360.
1928 Staff of Hedley Gold Mining Co. Concise account of mine and mill, Canadian Mining Institute, 1929.
1928 H. S. Bostock: Geology and Ore Deposits of Nickel Plate Mountain. Summary Rept. pt. *A*, Canadian Geol. Survey (1929). Surface map 1 to 1200.
1930–37 P. Billingsley: Reports to South American Development Co. and Kelowna Exploration Co. Surface maps, 1 to 1200; level and stope maps, 1 to 360; section grid, 1 to 360; models, 1 to 360.
1932–35 A. Locke: Unpublished studies on ore details.
1933–34 H. Schmitt: Unpublished studies of thin sections, rocks and ore.

6. *Eureka* (*Fig.* 7)

Eureka is a district of the third magnitude, producing lead, silver and gold from arsenical ores. It is 1 by 4 miles in area, and lies in the central part of the Great Basin in Nevada.

Its *stratigraphic column* includes the thick lower Paleozoic Great Basin section (mainly limestones) resting on the thick basal quartzite. These beds are here at a node of excessive deformation marked by a central, close, north-south anticlinal fold, which is overridden from the west by at least two thrust slices, and is intruded on its axis by a prong of basement quartzite. This prong, shaped as a crescent concave to the southward, is pushed up into the midst of shales and thin-bedded limestones. It emerges from the depths with steep contacts all around, but flattens near the present surface so that its crescentic horns extend far southward as shallow wedges.

Within the curve of these horns is a small *intrusion* of quartz monzonite. Other small intrusions are associated with thrust strands a mile north of the prong. Rhyolite dikes follow portions of the steep prong boundaries.

The quartzite of the prong, which is shattered and fractured, is flooded with *alteration.* Limestones, which rest on its back in successive unconformable thrust slices, contain *clusters of ore bodies* (Fig. 7*a*). These gather downward on thrusts and steep fissures to two inlets, both on the northern boundary of the prong (Eureka Hill and Richmond mines). Other lesser ore inlets are outside the prong; one (Holly mine) on the northern thrust strands above mentioned; a second (Croesus mine) on a fault that prolongs southward the eastern horn of the quartzite; and others (Diamond, Industry mines) in the great thrust blocks that ride over the southwest side of the district.

On Fig. 7 the dot-and-dash line, with the dip arrows, shows the general shape of a close sigmoid fold. Compression beyond the strength of the rock pile has further resulted in thrusting. This has produced: (*a*) the Prospect Mountain thrust block, which overrides from the west the southwestern loop of the sigma, and (*b*) the Ruby Hill thrust block, which rises upward on the nose of the northeast loop; forming an extreme example of resultant tensional *lengthening* along the axis made by a *compressive* fold.

Monzonite also has moved up along this same axis. Ore bodies are predominantly in the Ruby Hill thrust block, which is saturated with alteration minerals.

Sources of Information, Eureka

1884	J. S. Curtis: U. S. Geol. Survey *Monograph* 7. Geology of mines as of 1884; maps 1 to 4800.
1892	A. Hague: U. S. Geol. Survey *Monograph* 20. Areal geology of region; atlas.
1928	G. F. Stott: Geological maps of Holly mine, 1 to 600.
1927–28	Staff, U. S. Smelting Co.: Surface map of district, 1 to 2400; underground maps not available to us.
1928	P. Billingsley and A. Locke: Report to Western Pacific Railroad Co. on all mines of district. Surface map, 1 to 2400; mine-level maps, except on Ruby Hill, 1 to 600.
1928	H. M. Kingsbury: Report to Billingsley and Locke on Ruby Hill mines. Level maps, 1 to 2400.

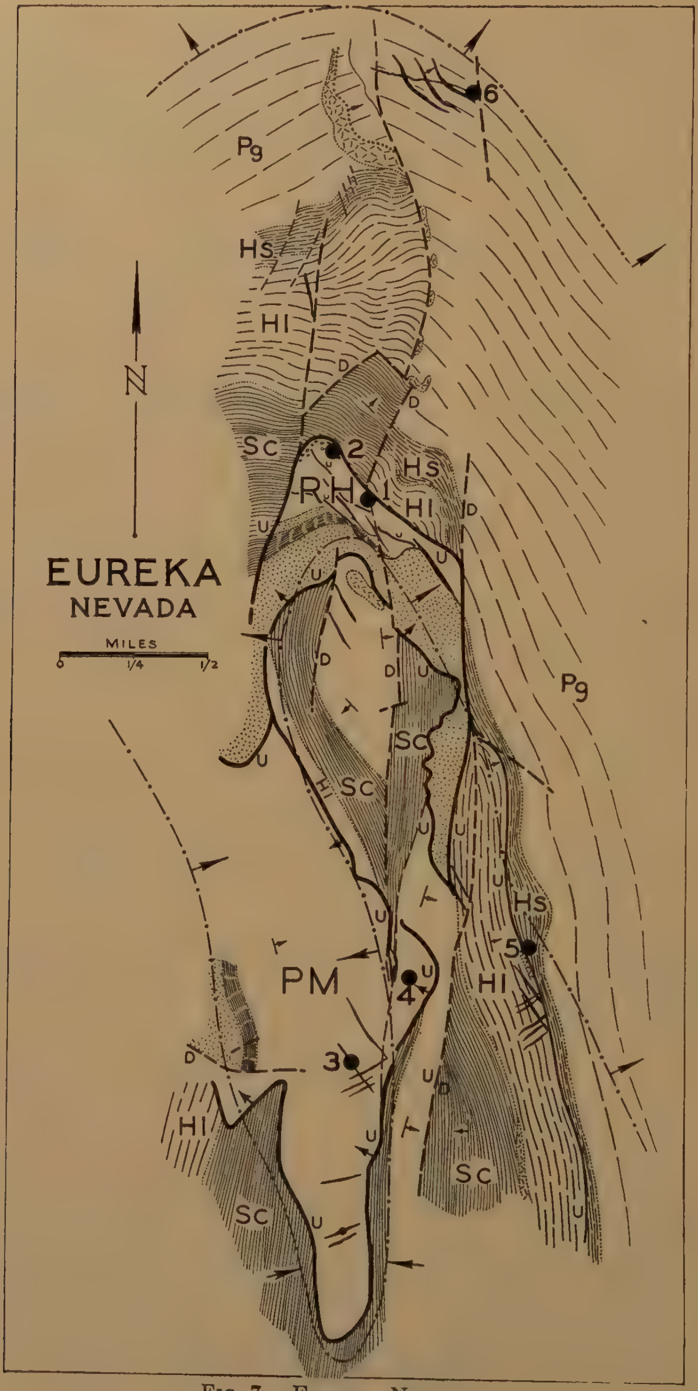

Fig. 7.—Eureka, Nevada.

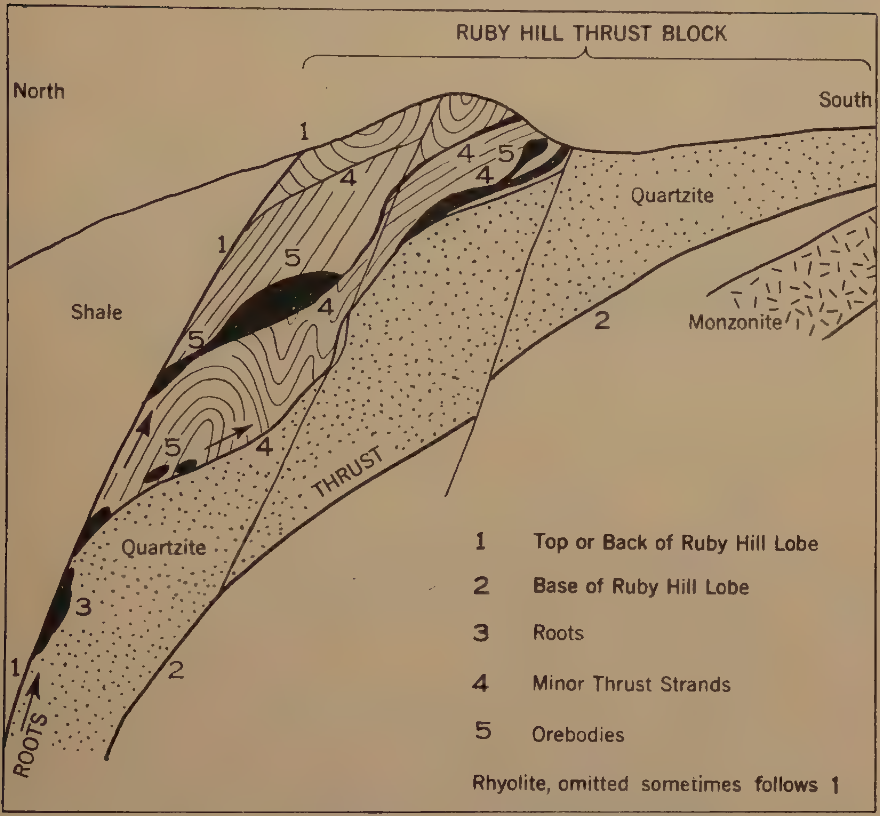

FIG. 7a.—EUREKA, NEVADA—RUBY HILL SECTION.

Formations:
- Dotted, Prospect Mt. quartzite—basal Cambrian.
- *PM*, Prospect Mt. dolomite.
- *SC*, Secret Canyon shale.
- Hachured, quartz monzonite.

Thrust Faults (shown by heavy lines):
- *RH*, Ruby Hill thrust block.
- *PM*, Prospect Mt. thrust block.

Normal Faults, shown by broken lines.

Hl, Hamburg limestone.
HS, Hamburg shale.
Pg, Pogonip limestone.

Ore Foci:
- 1, Eureka Hill.
- 2, Richmond.
- 3, Diamond.
- 4, Industry.
- 5, Croesus.
- 6, Holly.

7. *Ely* (*Fig.* 8)

Ely, of second magnitude, produces copper with minor gold from an area 2 by 4 miles in east-central Nevada.

Figs. 8 and 8*a* show the structures developed in soft and incompetent formations as these are squeezed and rolled by the northward motion of a strong roofing sandstone (Rib Hill) over an even more massive footwall limestone (Nevada). The weak members develop a crumpled trough on a west by north axis, and as the section shows, are

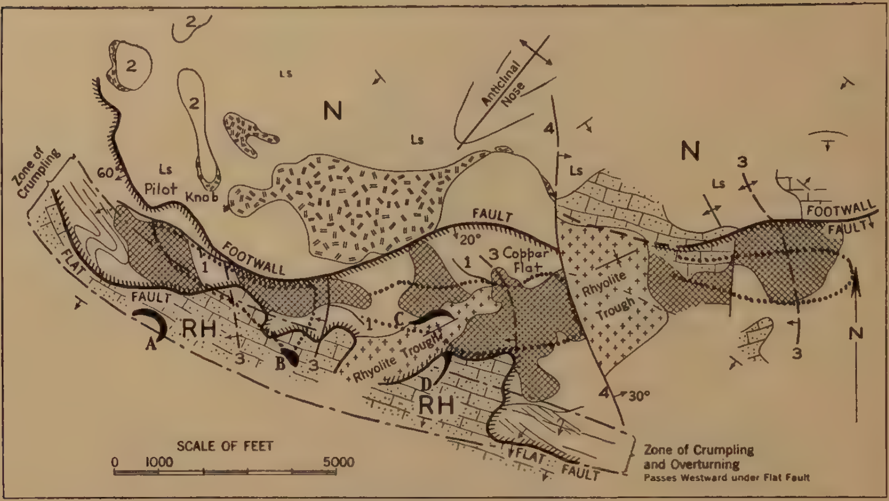

FIG. 8.—ELY, NEVADA—PLAN.

N, Nevada (Devonian) limestone north of trough.
RH, Rib Hill (Pennsylvanian) sandstone thrust over trough.
1, Mississippian limestone and shale in trough.
2, Mississippian limestone thrust outliers north of trough.
3, cross faults in trough.
4, late normal fault.
A, breccia roots under Alpha-Old Glory mines.
B, breccia roots under Richard Morris mines.
C, breccia roots under Emma mine.
D, breccia roots under Liberty pit ore body.
Crosshatching, ore porphyry.
Double hachures, peanut porphyry.
Crosses, rhyolite.
Dotted line, outer limits of ore bodies.

pinched at the bottom of this trough and *expanded* above. Into this expanded part are intruded chonoliths of Ore porphyry, which grow upward out of breccia roots and contain the ore bodies.

The *sedimentary formations* comprise a portion of the thick Basin Paleozoics from the Devonian to the Pennsylvanian; limestones mostly, with a shale and a sandstone member. These rocks have in general a dip to southwest and south, conforming to the plunge of a broad anticline; but in the district proper this is interrupted by a northwesterly strip of intense deformation. The strip is a narrow synclinal trough, with overturned south limb and minor axial wrinkles; all accentuated by faulting and all overridden from the south by a flat thrust sheet of Pennsylvanian sandstones. In the trough are Mississippian shales and thin limestones, while the footwall to the north consists of the massive Devonian limestone. The deformed strip is thus a structure developed mainly within weak beds caught between a massive basement and a

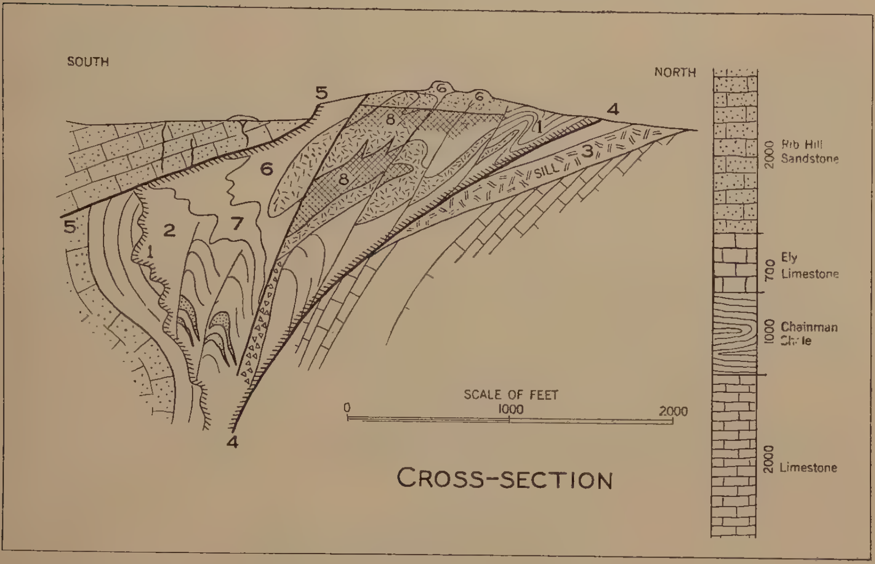

FIG. 8*a*.—ELY, NEVADA—SECTION.

1, limits of alteration funnel.
2, kaolinized limestone in trough.
3, peanut porphyry sheet.
4, footwall fault, north of trough.
5, flat fault, over top of trough.
Dash hachures, ore porphyry.
6, jasperoid replacement in trough and along fault strands.
7, pyrite-hematite replacement in trough.
8, ore bodies.

strong higher bed thrusting northward (Fig. 8*a*). Like the Bisbee syncline, the trough is broken at intervals by subordinate *cross faults*, and *intrusions* are abundant along it. They are of three periods: (1) Ore porphyry (pre-ore, altered), (2) Peanut porphyry (post-ore, fresh), (3) rhyolite (post-ore, fresh).

The Ore porphyry occurs in an alignment of chonoliths, which are in the shape of shallow expansions within the deformed weak beds of the strip. Each chonolith funnels down toward a breccia pipe root situated on a cross-fault intersection.

The Peanut porphyry is in the form of spreads, mainly in the flat floor made by the thrust that carries the Pennsylvanian beds northward over the trough and the Devonian footwall. It also occurs on thrust strands within the trough beneath the Ore porphyry. These latter occurrences show replacement of the altered beds by the porphyry minerals in fine laminae.

The rhyolite is mainly in the trough. It appears as dikes on fault strands and on the margins of inlet breccias; as sheets in the upper portion of the trough, *above* the ore porphyry; as a canoe-shaped body filling to the surface an over-deepened sector of the trough; and as extensive surface flows to the northward.

Alteration fills the trough, rising in funnels from foci at crossings, and spreading from rim to rim in the upper portion. Silicification and garnetization are widespread with pyrite and siderite and hematite in important masses also, traversed by a boxwork of veinlets. Oxidation of the pyrite masses has reduced huge sectors of the trough to the pasty clay residual from limestone.

Ore bodies are of two types: first and dominant are the funnels of "disseminated" copper ore in the crackled Ore porphyry chonoliths and adjacent garnetized beds. These funnel down, like the porphyry, to the breccia pipe inlets, and show near the roots a higher grade of primary copper. (Ruth, Liberty Pit, Emma, Morris mines.)

Second, and subordinate, are the clusters of ore in the limestones of the trough, south of and lower than the porphyry ores. These ore bodies are controlled by minor sharp wrinkles and by cross fault intersections. (Ruth Sulphide, Richard, Alpha mines.)

Sources of Information, Ely

1917 A. C. Spencer: U. S. Geol. Survey *Prof. Paper* 96. Compendium; surface map, 1 to 30,000.

1926–30 Staff, Consolidated Coppermines Corporation. Surface map, 1 to 1200; level maps in company mines, 1 to 480.

1926 R. Blanchard: Surface map, west part of district, 1 to 1200.

1906–28 A. Locke: Various visits, including Secondary Enrichment Investigation, 1914.

1929 P. Billingsley: Report to Consolidated Coppermines Corporation. Surface map of west part of district, 1 to 1200; level maps of company mines, 1 to 480.

1932 E. N. Pennebaker: Geology of the Robinson (Ely) District. *Min. and Met.* (April 1932) **13**, 163.

1933 A. M. Bateman: Copper Deposits of Ely, Nevada. Int. Geol. Congress, Copper Resources of the World (1933).

8. *Goldfield* (*Figs.* 9 *and* 9*a*)

This district, judged by structure and alteration, is nearly as extensive as Goodsprings, covering an area 4 by 12 miles. The third magnitude production of rich gold ore, however, has come from one square mile in the southwest corner of this area. The district lies in southwest Nevada, toward the California line.

The *formations* are Tertiary volcanics, resting on a metamorphic Paleozoic basement. The volcanics comprise fragmentals with sparse flows interrupted by thin horizons of fine water-lain tuffs and muds. The basement rocks are limestones, lime argillites and slates, with belts of granite and alaskite. Steep dips on northeasterly axes predominate in the basement beds at Goldfield. Thirty miles to the southwest, at Silver Peak, they assume the northwesterly Sierra trends. Between is the Walker line of northwest faulting.

The Tertiary cover rocks show deformation by renewal on all these trends, but principally on the Walker line. This has produced widespread stretching in the region to the north, marked by the pulling apart of west-dipping blocks along flat east-dipping normal faults, a structure characteristic of Comstock and Tonopah as well as Goldfield. It is, in fact, a late Tertiary Great Basin structure, found widely in the hinterland of the Cordilleran thrust arc. Along the Walker line the Tertiary beds are traversed by great northwest reticulated and echeloned faults, with complementary east-west dragfolds and steep north-south tension fissures.

In Goldfield proper the combined structural elements are:

South edge: zone of Walker faults, with associated thrusting to the northward.

Adjacent on north: strip of east-west folds (Mohawk nose, etc.) in a region of general westerly dips.

Intersecting these folds: (*a*) east-dipping normal stretching faults, (*b*) steep tension fissures, (*c*) northeast faults on rejuvenated basement axes.

Intrusives are in three groups: the earlier, dacite; the middle, andesite; and the later, rhyolite. The dacite occurs in flat-bottomed chonoliths injected probably along thrusts that accentuate the east-west fold structures; thickest in the trough next the Walker faults, and wedging out northward as the folding dies. The andesite has its roots in this trough also, but divides, part coming in under the dacite and part over it, with connecting dikes traversing the dacite. The rhyolite is still further skeletonized, forming a boxwork through the district with panels following Walker faults, flat normal faults, thrusts, and the weaker tuff partings of the volcanic pile of rocks. It is the latest pre-ore intrusive.

Alteration occurs in a belt a mile wide along the Walker faults, with comblike extensions along the east-dipping and northeast faults to the northward. It gathers into larger funnels in the structural corners made by these elements with the Walker fault zone. Alunitization and silicification are the important phases, of which the latter is the more specialized. The silicified "lodes" are locally intensely folded.

Ore bodies are clusters, occurring mainly on late fissures traversing certain folded portions of the boxwork of silicification. The main grouping occurs on the Mohawk folds at their intersection with a specific east-dipping, normal, stretching fault, the Consolidated Lode. With roots in the basement, the ore bodies spring upward along the trace of the lode and the folds; expand widely where this leaves the lower fragmental beds and enters the dacite chonolith; and finger out toward the top of this intrusive mass. From compact roots at a depth of 1500 ft. the ore branches until its fingers, near the surface, have a spread of ½ mile. Lesser clusters have recently been found in parallel, normal, stretching faults to the east of the Consolidated Lode, where these in turn intercept the Mohawk folds.

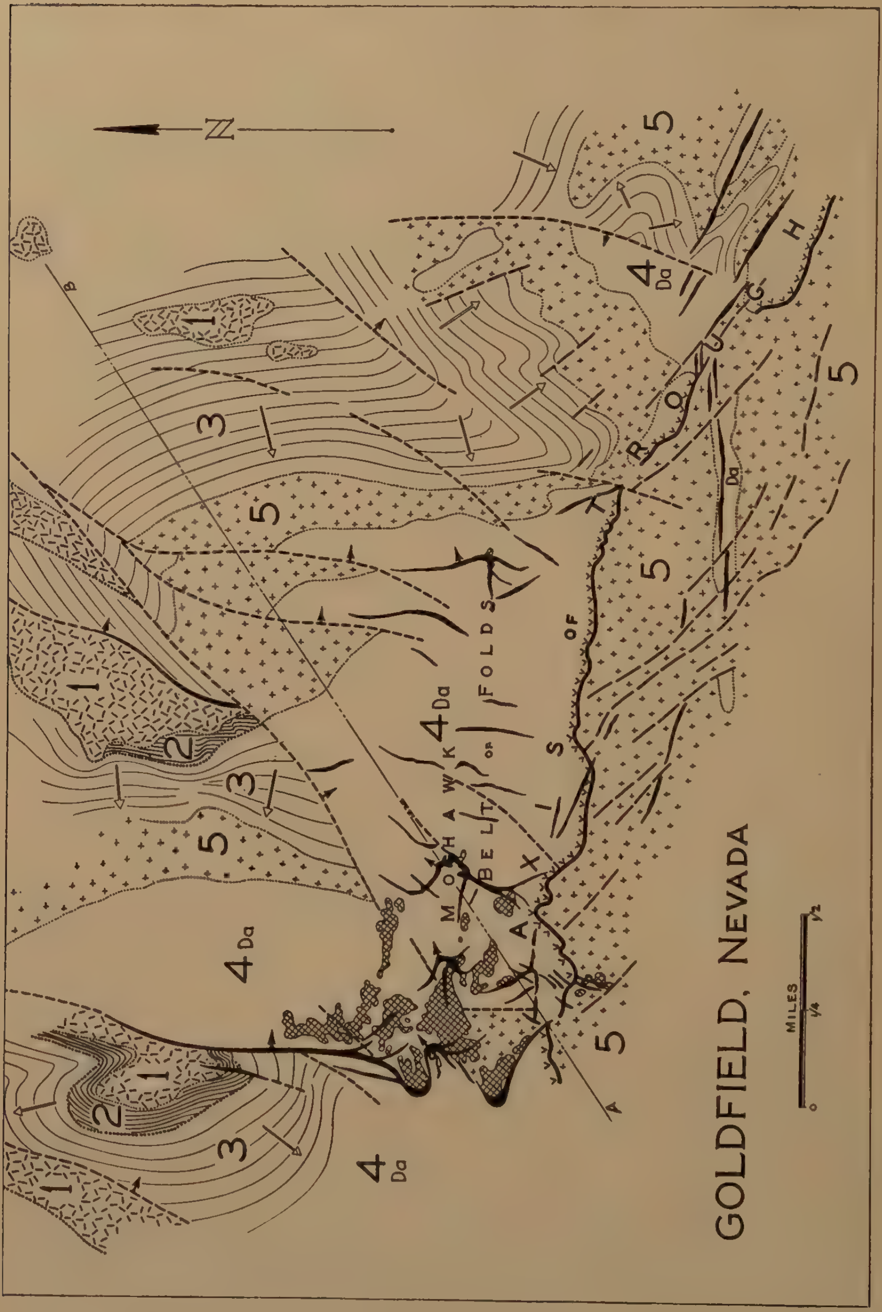

FIG. 9.—GOLDFIELD, NEVADA—PLAN.

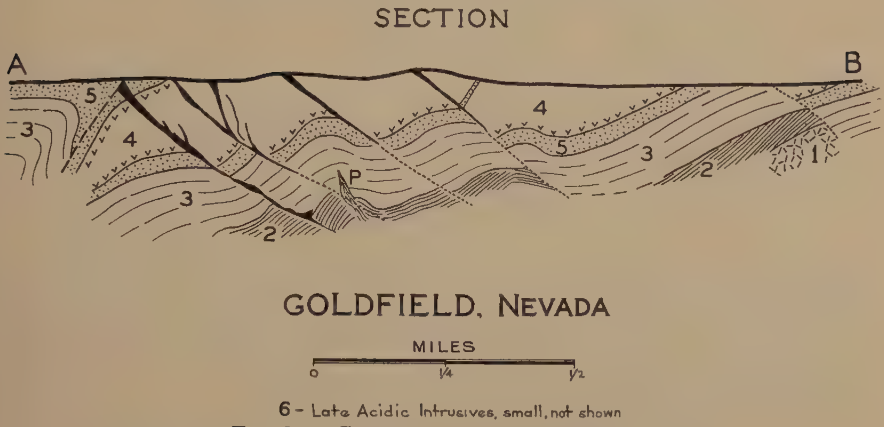

FIG. 9*a*.—GOLDFIELD, NEVADA—SECTION.

1, basement granite, intrusive into 2.
2, basement slates, Paleozoic.
3, bedded effusive tuff and latite, Tertiary.
4, dacite, intrusive into 3, steep to overturned south contact *checked.*
5, andesite, intrusive between 3 and 4, and above 4.
6, thin rhyolite sheets, intrusive between 2 and 3, and between 3 and 5, *not shown.*
Heavy black lines, quartz-bearing lodes, flat, east-dipping.
Dash lines, Walker-line faults, steep south-dipping.
Dotted lines, normal faults, mostly flat east-dipping.
Crosshatching, stoped ore bodies, rising from east to west on quartz-bearing lodes.
P, on section, Fig. 9*a*, slate prong pushed into latite on Mohawk nose.

Fig. 9 shows the structures produced by motion along the Walker fault zone, which is represented by the northwesterly dash lines in the southern part of the map. On this zone the south side has moved northwest, the north side southeast. This motion has a *compression* component from north to south, and a *tension* component acting from east to west. The compression is expressed by *folds* and *overthrusts;* a trough close to the Walker fault zone, overridden by thrusts from the south and more open folds parallel to the northward (Mohawk belt of folds). The dacite intrusion is focused along the trough. The tension is expressed by north-south flat, east-dipping faults, by means of which the west-dipping formations have been *stretched.* The *lodes* follow these, and have been in turn folded on the compression axes.

Other structures, inherited from the *basement,* are present; mainly northeast faults.

Sources of Information, Goldfield

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1910	A. Locke: Underground maps of Goldfield Consolidated mines, 1 to 480.
1907–20	Staffs, Goldfield Consolidated Mining Co. Underground maps, stoping and sample records.

1932 H. A. Schmitt and A. Locke: Surface map, 1 to 1200; compilation of stopes and sections.

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Regional Patterns

Just as the ore bodies described above can be grouped into clusters under common structural control, so with adequate information can districts be fitted into unit regional patterns. For example:

Colorado: Leadville, Alma, Red Cliff, Climax; Breckenridge, Georgetown, Idaho Springs, Central City.

New Mexico: Silver City, Santa Rita, Hanover.

Arizona: Superior, Miami, Globe.

California: Mother Lode, Grass Valley, Allegheny.

Nevada: Goldfield, Tonopah, Silver Peak.

Utah: Park City, Bingham, Tintic.

Montana: Phillipsburg, Butte, Helena.

Essential for building these larger units is detailed mapping of the regions between districts. In this, mining geology is still far behind the work inside the districts. The beliefs that such regional mapping may disclose new, hidden districts, just as district mapping has disclosed new, hidden ore clusters, will inevitably, however, force progress in the larger field.

To illustrate regional patterns, we may consider the Salt Lake area, where the Uinta Mountain axis, intersected by the Cordilleran thrust zone, makes an outstanding geologic crossroads.

Salt Lake Crossroads (*Fig.* 10)

The mining districts whose structure is made up of elements of the Salt Lake crossroads include Park City, Cottonwood, Alta, American Fork, Bingham, Stockton, Ophir, Mercur and Tintic.

Park City lies on the north limb of the Uinta axis, where this is disturbed by the most easterly Cordilleran thrusts. The Uinta Mountains, like so many of these rejuvenated early uplifts, have a cross section showing a broad flattish crest, turning down on the margins to steep limbs, which may become overturned or even overthrust. The Park City district covers the northern half of this flat crest, and so has formations with gentle northerly dips except where modified by Cordilleran deformation. Along the axis proper are aligned granitic stocks and chonoliths with overhanging contacts on the north side.

The Cordilleran modifications consist of north-south folds, culminating in overthrusts and in northeasterly tear faults, with associated tension cracks (see Fig. 13). Dikes follow the tears, and ore mineralization occupies the tension cracks, spreading from these to form mantos at one major and several minor favorable horizons (Jenney ore bed, etc.)

Cottonwood and Alta lie to the west of Park City, and have similar structures, which, however, involve more westerly Cordilleran thrusts and lower formations. Also, their ore mantos generally follow thrust planes. American Fork district covers mineralization on the same Cordilleran thrusts, but on the south side of the Uinta axis.

Bingham, again, is on the north Uinta limb, on the west side of the downfaulted trough which forms the Salt Lake Valley. Its formations, like those at Park City, have northerly dips, but here they turn down, within the district proper, into the steep and overturned north limb. Two monzonite stocks are found just south of the steep flexure. They exhibit, like the Breece Hill porphyry at Leadville, a strong tendency to *spread* at certain beds and bedding-fault planes.

The Cordilleran deformation affects this relatively simple flexure by superimposing northwest folds and faults and northeast tear faults (Carr Fork, etc.). The Cordilleran folds lie mainly to the west of the district proper, but such associated phenomena as minor crumpling and differential sliding between beds are vitally important in forming the ore channels. These are canalized in three or four main horizons, made by weak limestone layers within the massive Pennsylvanian quartzites. In the easternmost porphyry stock, also, is the "disseminated" copper orebody of the Utah Copper.

Stockton lies 10 miles west of Bingham, on the same steep north Uinta limb, which is cut by a group of northwest faults and dikes. As in Bingham, intercalated limestone beds contain the ore, which here spreads out only slightly from the fault-dike intersections.

Ophir, 10 miles south of Stockton, has its ore bodies on a northwest Cordilleran anticline sliced by a northeast tear (?) fault; while Mercur is found still farther south on the east limb of this same anticline.

Tintic, described in an earlier section of the paper, lies 40 miles south of Bingham well toward the southern Uinta limb. Its northeast open folds, the Tintic syncline and the East Tintic anticline, probably began as pre-Tertiary Uinta elements. These were compressed from the west by Cordilleran thrusting, forming the steep western limb and the minor crumples and thrusts farther east, and were sliced by the southeasterly tear faults along which the southern blocks moved eastward. Just as Bingham and Park City reflect in their tear structures the differential progress of Cordilleran deformation on and north of the Uinta crest, so does Tintic reflect this on the south side. All result from the complex adjustments necessitated by the intersection of the north-south Cordilleran thrust zone 60 or 70 miles wide, with the resistant uplifted mass of the east-west Uinta uplift 40 miles wide.

Fig. 10 shows the principal structures produced by the intersection of the eastward-thrusting Cordilleran mountain belt and the resistant high block of the older Uinta uplift.

In general, the Cordilleran belt is retarded and buckles into "accordion" folds against the end of the Uinta axis, and slides forward on either side, with the development of tear faults. A separate basin of Tertiary clastic deposits is found on each side of the Uintas.

The intersection is a focus of Tertiary intrusives, volcanics and ore deposits, one cluster lying on the Uinta axis (Cottonwood-Alta-Park City), one on the steep north Uinta flank (Bingham-Stockton), and one toward the south flank (Tintic).

Sources of Information, Salt Lake Crossroads

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1920–31 P. Billingsley, T. Lyon, P. R. Murphy, and others of International Smelting Company's Geological Department. Mapping of mines in Park City (all); Bingham (Utah Consolidated, Utah Apex, Utah Metals; Tintic (all except Mammoth); Stockton, Ophir, Mercur.
1924 R. N. Hunt: *Trans.* A.I.M.E. (1924) **70**, 856. Bingham.
1927 J. J. Beeson: Mining Districts and Relation to Structural Geology. *Trans.* A.I.M.E. (1927) **75**, 757.
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See also *Sources of Information, Tintic.*

Montana Echelon Gap (*Fig.* 11)

The nature of a unit regional pattern is also well illustrated in Montana, in the west central region which we call, structurally, the Montana Echelon Gap.

Butte is central to this region, and its structures provide leads to the larger elements. Dominant, in Butte, are northwest steep tear faults, on which the movement, nearly horizontal, has pushed the south side toward the southeast. Secondary, are east-west and east-by-north fissure veins, essentially tension cracks complementary to this southeast tear faulting (Fig. 11). In depth east-by-north tension cracks pass into east-by-north echelons of northwest horsetail veinlets, an alternative expression of the same stresses.

These structures exist within a mass of granitic rock, the Boulder batholith, whose internal patterns suggest that north of Butte it is mainly a west-dipping *spread*, while south of Butte it is mainly a steep northwest and southeast-striking crosscutting *intrusive*.

Its eastern edge, which is the base of the spread, is straight and commonly shows the adjacent Paleozoic and Algonkian formations to plunge westerly beneath the granite; its western edge, on the contrary, is sinuous, and shows that the Cretaceous sandstones and andesites on that side normally *cap* the granite. The mass of the Boulder batholith thus lies in the rock column essentially where elsewhere in central Montana we

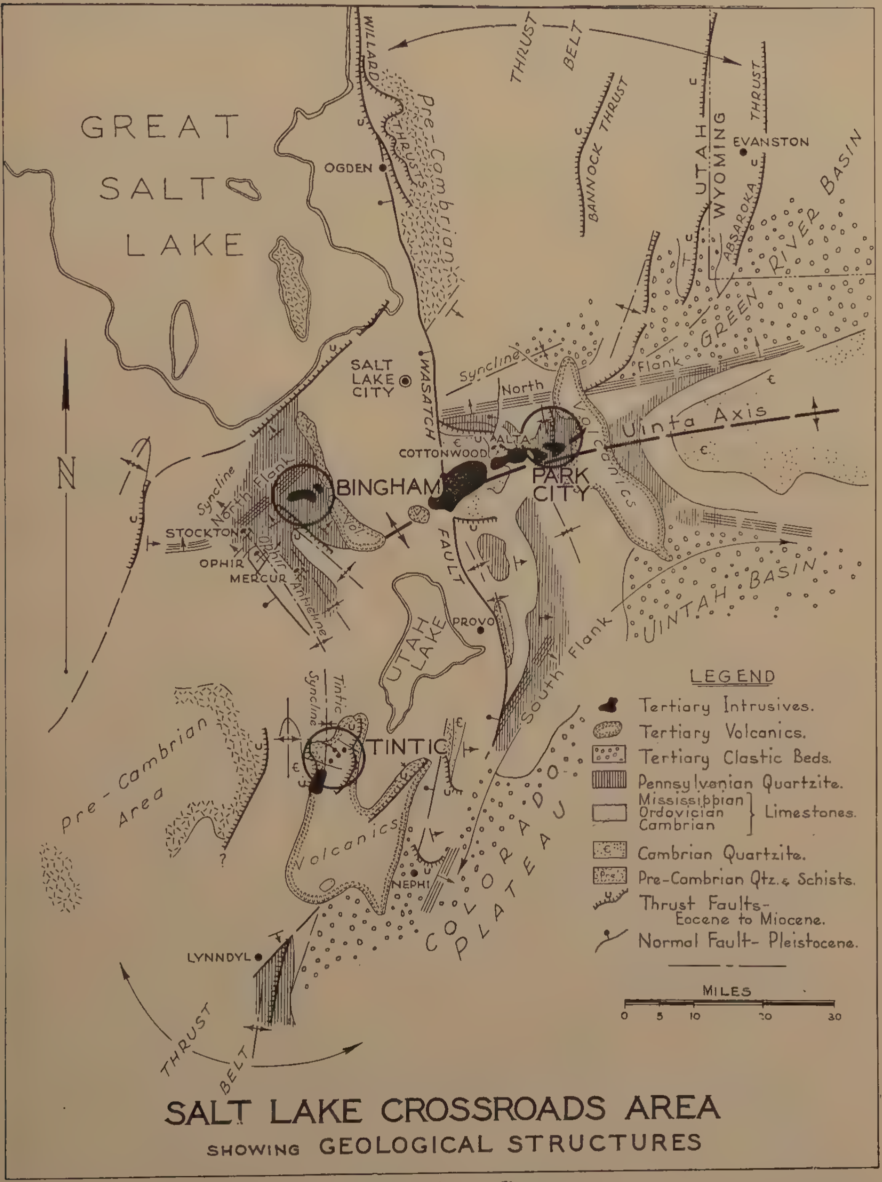

FIG. 10.—SALT LAKE CROSSROADS.

find thick Cretaceous shales. It is dominantly a crosscutting intrusive only south of Butte, and particularly at its southeast corner, where it rises through pre-Cambrian and lower Paleozoic formations. This is the *keel*, which is prolonged farther southeast by a long strip of granite traversing the Archean horst of the Tobacco Root Mountains toward Yellowstone Park.

Thus, the steep *northwest* fault veins of Butte harmonize with the steep keel portion of the Boulder batholith and this in turn leads into the northwest horsts, which hold up basement formations across the Yellowstone Park region—huge basement prongs marking rejuvenation of an early uplift.

The *east-by-north* tension veins of Butte similarly harmonize with larger features. They carry, in the district, quartz porphyry dikes. These are found to be the local representatives of a Tertiary dike zone which is traceable westerly and southwesterly from Butte into Idaho. This is just such a zone as the well-known dike and mineral belt of the Colorado Front Range, which is formed by rejuvenation of structures in the basement dating from the late pre-Cambrian orogeny. This Montana zone may be rejuvenation of Final Paleozoic trends.

The *spread* portion of the Boulder batholith is elongated in a north-by-east direction. This is the trend of the sedimentary folds and thrusts in the region northwest of Yellowstone Park, and the batholith occupies a major syncline of this system, immediately east of the principal thrust zone. The north-by-east direction is local to central Montana, forming a diagonal link in the Cordilleran thrust zone between the northwest-southeast trends which predominate in northern and southern Montana. In each case the turn to the normal trends is marked by northwest fault lines; the Absaroka line on the south side extending southeast along the Yellowstone horsts, and the Helena-Missoula line on the north side extending northwest to Spokane. The two may be regarded as echeloned members of a northwest tear fault zone of continental scale which we call the *Lewis and Clark line.* The echelon gap, formed where the fault zone crosses the Cordilleran thrusts and breaks over to the Yellowstone horsts, is the regional structure in which the Boulder batholith has been developed. A complex of continental crustal movements has made this a preferred focus of intrusion, alteration and ore deposition.

The map of Fig. 11 assembles the structures that lead to and intersect in the Montana Echelon Gap area.

On the western edge is the Idaho granitic batholith, which in the area shown, adjacent to the Bitterroot Valley, is a replacement gneissic product full of residual schists. It has a north by east anticlinal structure, as shown, rolling wavelike behind the thrust plates that lie to the eastward.

These, which include the Philipsburg and Deer Lodge Valley thrust faults, mark the western limit of Mesozoic formations and carry Algonkian argillites across the dragged-up Cretaceous shales and sandstones. The thrust zone, therefore, must mark a Mesozoic uplift and source of sediments which has been rejuvenated with Tertiary deformation.

Immediately east of this thrust zone is a syncline of Cretaceous beds, into which is emplaced the Boulder batholith. East of this in turn are parallel north by east folds steep on the east limbs and exaggerated by overthrusts. The last of these folds overrides the margin of the great Crazy Mountain post-Cretaceous syncline, which is the foreland involution of the Rocky Mountain front proper.

This system of north by east folds, thrusts and intrusions, which extends in this way from the Idaho line to the plains, has no great length from north to south. At both edges the structures turn into a northwesterly-southeasterly direction, which is that of the Cordilleran mountain belt across Canada and as far south as Utah. This Montana system is therefore an *interruption*, or *inhomogeneity*. It is further isolated by faulting; the Lewis and Clark tear faults outline it on the north, dying out toward Helena into dragfolds; and on the south an echeloned offset of the same tear fault shows feebly south of Butte but strengthens into the Absaroka fault along the north front of Yellowstone Park. A keel of the Boulder batholith extends southeasterly along this zone.

In brief, the Cordilleran mountain belt is swirled into a sigmoid fold on which the Lewis and Clark tear fault is echeloned from the northern to the southern limb, and the Boulder batholith has spread into the core of the fold, displacing mainly soft Cretaceous shales.

Principal Sources of Information, Montana Echelon Gap

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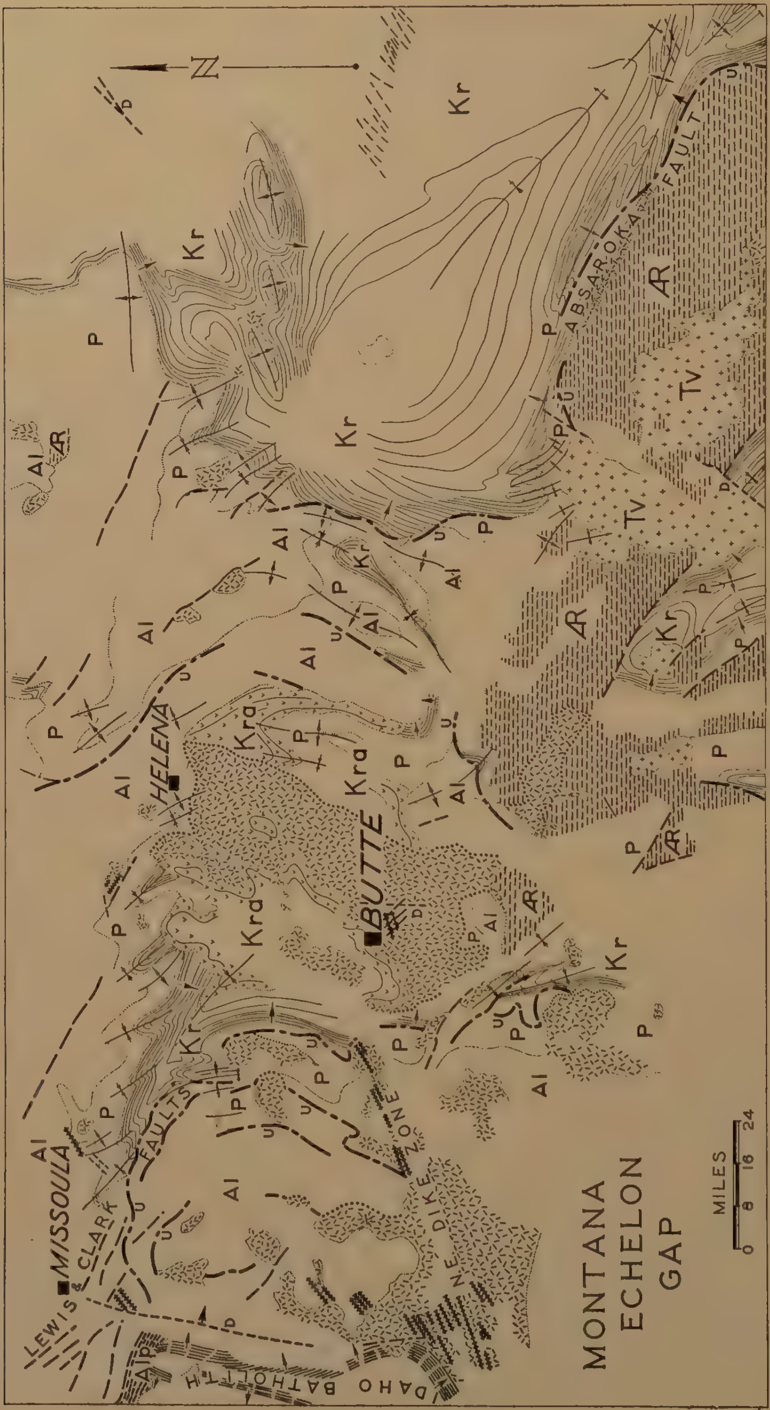

FIG. 11.—MONTANA ECHELON GAP.
Legend on opposite page.

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1921 P. Billingsley and T. Lyon: Geologic Mapping of Oil Structures in Musselshell, Yellowstone and Big Horn Counties. Reports to Anaconda Copper Mining Co.
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1935 W. T. Thom, G. M. Hall, C. H. Wegemann and G. F. Moulton: Geology of Big Horn County and Crow Indian Reservation. U. S. Geol. Survey *Bull.* 856.
1934 F. F. Grout and R. Balk: Internal Structures of Boulder Batholith. *Bull.* Geol. Soc. Amer.
1920–36 C. H. Clapp, C. M. Langton and others: Publications of Montana State Bureau of Mines and Geology.
1936–37 W. T. Thom, Bucher and others: Yellowstone-Big Horn Research Assn.

CONTINENTAL FRAMEWORK (FIG. 12)

The foregoing analyses serve to illustrate the manner in which, as facts become available, district structures fit into the larger continental framework. The motions represented in the districts are local phases of the crustal movements of the continent.

These continental movements are not haphazard; they are *systematic* in time and place. They occur predominantly in definite *places*, and recur at intermittent *epochs of orogeny*. The full pattern of folds, faults, uplifts and associated erosional dumps of coarse detritus made by each successive epoch will, we believe, be successfully deciphered in the future by detailed regional mapping, supplemented by drill data and the inter-

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FIGURE 11

Ar, Archean basement complex.
Alp, Algonkian, lowest member (Pritchard).
Al, Algonkian above Pritchard.
P, Paleozoic and Jurassic.
Kr, Cretaceous sediments, contoured.
Kra, Cretaceous andesite, equivalent to upper portion of sediments.
Tv, Tertiary volcanics.
Hachured, granites: heavy dotted contacts, steep or overhanging; light dotted contacts, flat, under cover rocks.
Lines and arrows show folds.
Dash lines, faults with Lewis and Clark strike. Dot and dash, thrust faults.

pretation of geophysical studies. At this time the general patterns only can be vaguely seen, with sparse bright spots here and there marking the localities where tectonic study is more advanced. But, dim as it still appears, the pattern of North American orogenies forms the essential framework for the ore deposits.

1. *Archean Orogenic* belts are found on the Canadian shield, which they traverse in southwesterly lines of deeply eroded mountain roots. They abound in unsolved problems of correlation and structure.

2. *The Late pre-Cambrian Orogeny* can be identified in southern Quebec. It makes an arc to the northward around Lake Huron, with Sudbury at the point; then passes westward through the Michigan iron ranges and under the Great Plains to the Black Hills, where it seems to turn sharply southward. It reappears again in the iron districts of eastern Wyoming, traverses the Front Ranges of Colorado, and shows intermittently in New Mexico and Arizona (Mazatzal Range) as far as Jerome. From Sudbury to Jerome the trends in these pre-Cambrian mountain roots are southwesterly or north-south. In western Arizona and throughout the Pacific States, however, they are northwesterly, so that this orogenic system grew as a V, enveloping the then Continental shield from Labrador to Arizona to Alaska. Inside this V are found its dumps of conglomerates and coarse sandstones, as well as foreland uplifts such as the Uintas and Yellowstone Park.

3. *An Early Paleozoic Orogeny* can be recognized in Quebec and New England, and again along the Pacific Coast. In the latter region it was *superimposed* on the late pre-Cambrian, but in the east the action had *retreated* southeastward, off the shield.

4. *The Final Paleozoic Orogeny* was again continent wide. It formed the Appalachians, the Arbuckles and Ouachitas; traversed southern New Mexico and Arizona, with a spur into Colorado; raised again the early Paleozoic Sierra Nevadas; swung northeasterly across Oregon (Blue Mountains) and finally renewed the northern Coast Ranges in Idaho, Washington and British Columbia. The clastic fans of this system make the Appalachian and Middle Western coal measures, the earlier red beds of Colorado and the Southwest, and the upper Pennsylvanian quartzites and conglomerates of the Great Basin. In this orogeny, in the west, the great *Pacific Echelon* first becomes noticeable, with the Oregon arc linking the complex masses of the Sierras and northern Coast Ranges. In these masses formed by superimposed orogenies there is a great development of *granite*. In the east, the Final Paleozoic orogeny again shows a retreat off the shield.

5. *The Early Cretaceous Orogeny* has in the east retreated to the West Indies, extending through Cuba into Honduras. Turning up the Pacific line, it traverses Sonora and southwest Arizona, and is superimposed on the Sierra Nevada complex. The Oregon arc is advanced southward

into northwestern Nevada, linking up through Idaho with the northern Coast Ranges. This orogeny greatly advanced the granitization of the Sierra Nevadas, Idaho, and the north coast. The advance of the Oregon arc into the Great Basin must have been accompanied by tear faulting on both Walker and Lewis and Clark lines. The Early Cretaceous clastic fans are found in Cuba, throughout the Southwest and the eastern Great Basin, and the eastern Rockies of Montana and Canada.

6. *The Early Tertiary Orogeny* is found only in western North America, for the eastern arm has retreated to the Caribbean. In the west it is superimposed on the Sonoran and Arizona belts of earlier orogenies, jumps the Walker line to form the Cordilleran thrust zone across Nevada, Utah and Southern Idaho; and, broken again by the Lewis and Clark line, makes a new belt of mountains (Canadian Rockies) east of the old north Coast Ranges. The expansion of the *Pacific Echelon* is marked by the advance of the Cordilleran belt of thrusts to the eastern margin of the Great Basin, accompanied by strong tear faulting on both Walker and Lewis and Clark lines and by stretching in the western Great Basin. In addition to these main orogenic elements, this early Tertiary orogeny enlivened the entire western part of the continent. Sectors of earlier mountain belts were rejuvenated (north Coast Ranges), old foreland domes were sharpened into horsts wedged up between thrusts (Colorado Front Ranges, Uinta Mountains), old roots were re-sheared. A new structure element, undoubtedly active much earlier, can also be recognized; a strong northwesterly tear line on the south Pacific Coast, showing motion of the continent southeastward with respect to the ocean. This we call the Anza line. The clastic dumps include the great lower Tertiary conglomerates in Colorado, Utah, Wyoming and Montana and the Tertiary clastics in troughs along the tear faults.

7. *The Parade of Orogenies* may be briefly expressed in terms of motion as shown in Table 1. To simplify still further, we can note that the two

TABLE 1.—*Parade of Orogenies*

Period	Pacific					Atlantic
	North		Great Basin[a]		South	
Late pre-Cambrian	Coast range	Lewis and Clark line	?	Walker line	Sierra Nevada	S. margin of Archean shield
Early Paleozoic	Superimposed		W. Oregon link		Superimposed	Retreat to N. New England
Final Paleozoic	Superimposed		E. Oregon		Superimposed	Retreat to Appalachians
Early Cretaceous	Superimposed		Nev.-Id. link		Superimposed	Retreat to Cuba
Early Tertiary	Superimposed and adv. to east		Cordilleran		Superimposed	Retreat to Caribbean

[a] See Fig. 12.

masses of superimposed orogenies; i.e., the north coast and Sierra-Nevada, lie in echelon along the Pacific coast, like drag folds made by the southeastward movement of the continent. And that this same movement is marked by a minor southeasterly advance of orogenic arcs into and across the Great Basin, which lies *between* these masses, and by a major southeasterly retreat of the contemporary Atlantic arcs. In all cases orogenic activity has spread *equatorward.*

Fig 12 is intended to show what is meant by the successive advances of an orogenic belt; in this case, the Oregon arc of the western United States, which has advanced from Oregon to eastern Utah, between the limits of the Lewis and Clark tear fault on the north (Spokane to Yellowstone Park), and the Walker tear fault on the south (Reno to Boulder Dam region).

As can be seen, the crust itself has not moved the entire distance. It buckled and thrust eastward to some extent in the first folding (late pre-Cambrian) and then froze into the rigidity of a completed mountain belt. Its clastic deposits spread eastward over the present Great Basin area. These clastics in turn were involved in the second and more easterly folding, which in turn froze. And so on through the series.

Fig. 13 shows in a very generalized way the composite pattern made by the successive orogenic belts in the United States.

The belts are readily differentiated east of the Rocky Mountains, occurring there in a well separated series which retreats southeastward off the Canadian shield into the Caribbean region. In and west of the Rocky Mountains, however, they are partly superimposed and difficult to disentangle. The earliest, late pre-Cambrian, turned north from a vertex in Arizona and seems to have extended up the coast. It cannot, however, now be distinguished there from the Early Paleozoic orogeny, which has left a trail of metamorphics of Ordovician and earlier age from southern California to Alaska.

By Final Paleozoic times the Pacific coastal region showed a three-part structure, made up of the Sierra-Sonora complex on the south, the north coast complex on the north, and the Oregon arc spanning the gap between these two echeloned massives. Subsequent orogenic activity, in Early Cretaceous and Tertiary times, increased the complexity of the massives, but shows on the map mainly because of the advance of the Oregon arc across Nevada and Utah, in a bulge bounded on north and south by northwesterly tear lines (Lewis and Clark, and Walker lines). Minor advanced Tertiary arcs are apparent in Wyoming, Colorado and New Mexico, where they both sharpen older tectonic structures and bulge between old high masses. A major tear line (Anza) parallels the California coast and bounds the Sierra-Sonoran block, which has moved southeastward relative to the ocean.

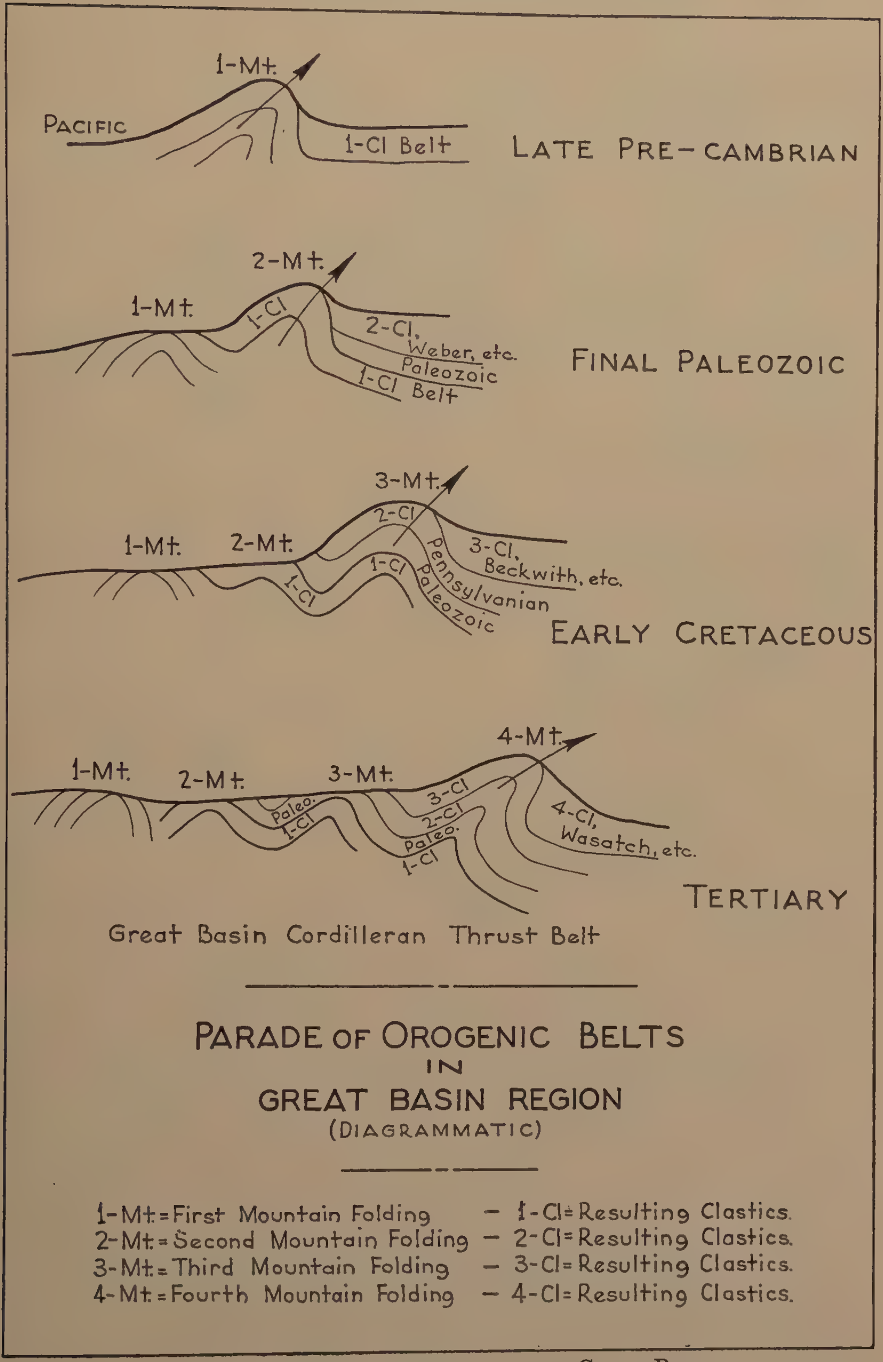

FIG. 12.—PARADE OF OROGENIES ACROSS GREAT BASIN.

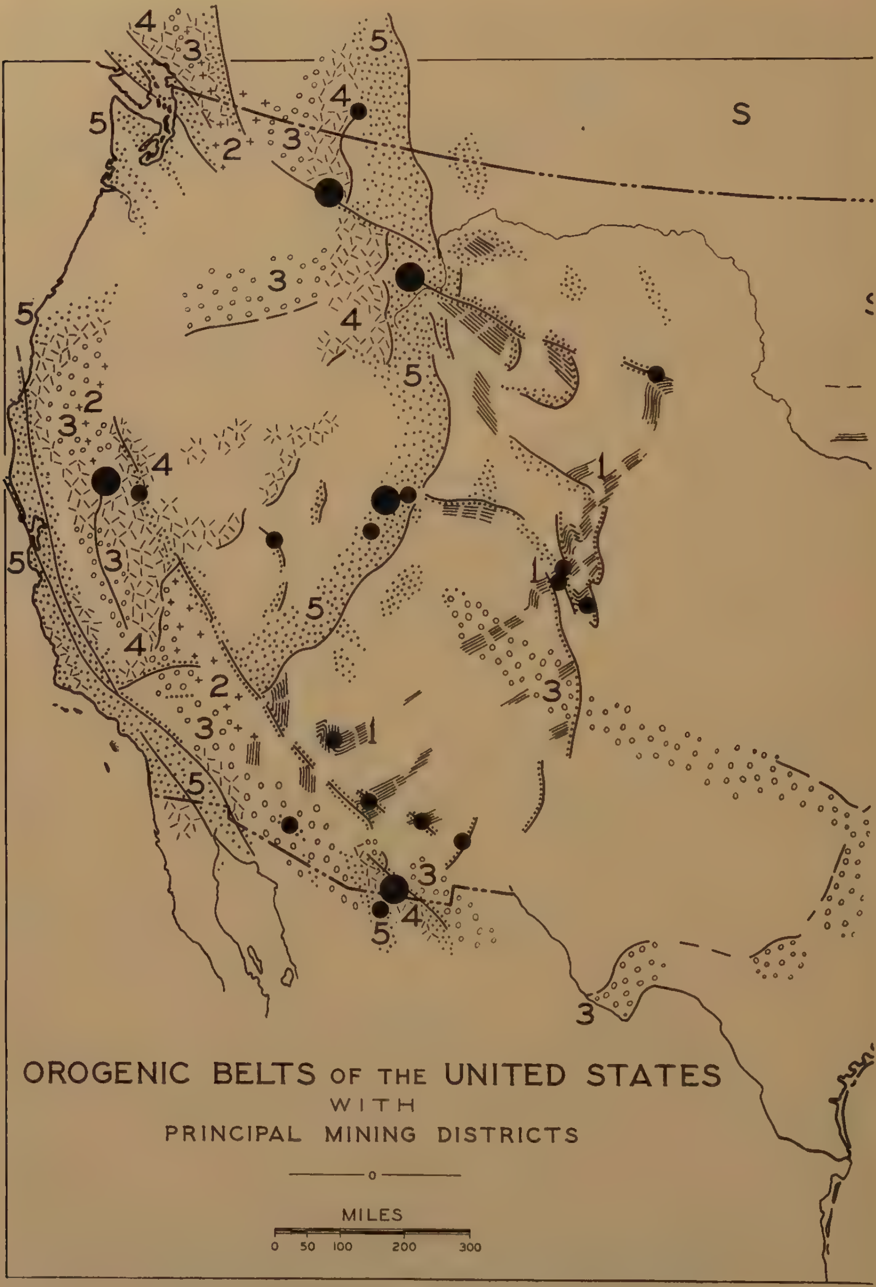
S
5
4
3
2
1
OROGENIC BELTS OF THE UNITED STATES
WITH
PRINCIPAL MINING DISTRICTS
MILES
0
50
100
200
300

FIG. 13.—OROGENIC BELTS OF THE UNITED STATES.

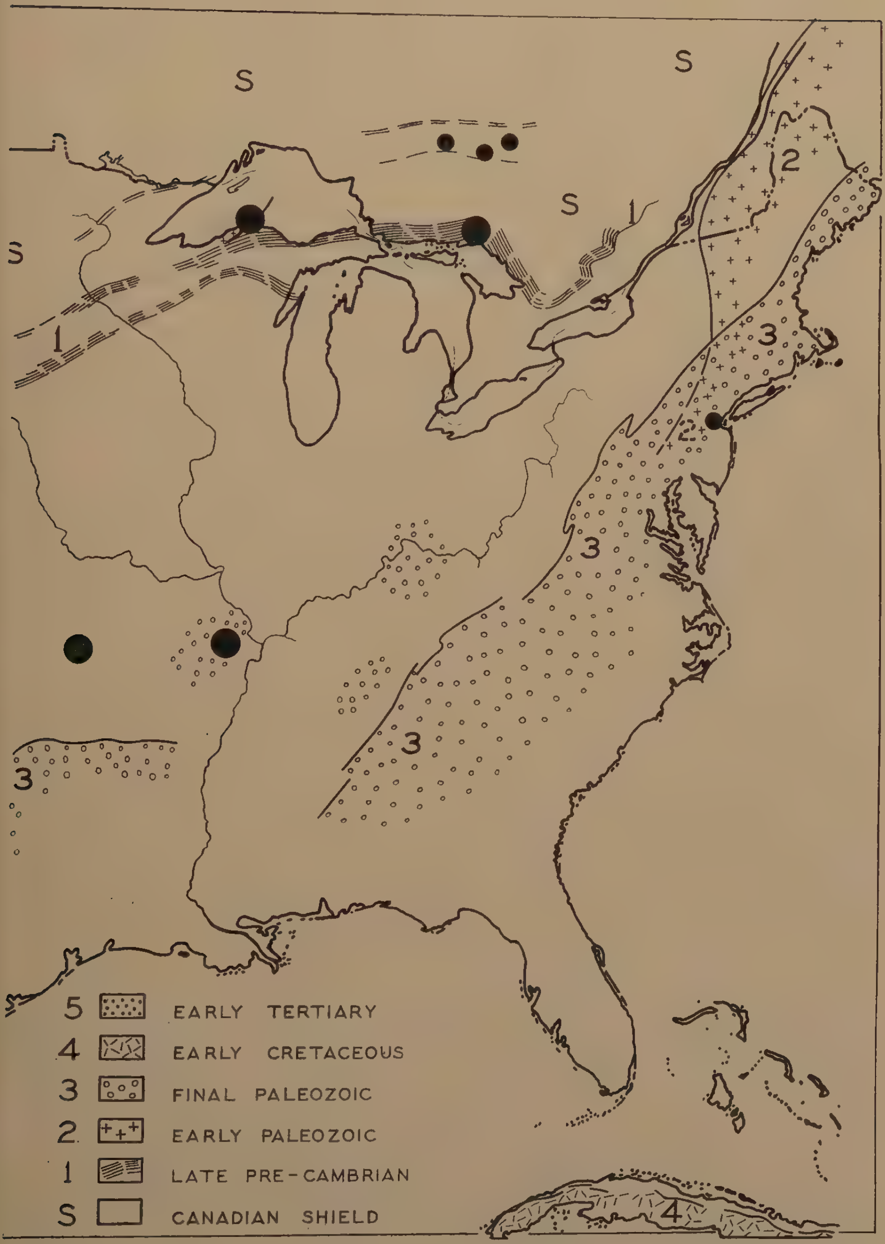

FIG. 13.—(CONTINUED).

Sources of Information, Continental Framework

It is impossible to list in full the sources from which the stratigraphic-tectonic picture of the continent has been built up.

Billingsley has been assembling such data since 1922, when he found it desirable, in connection with oil exploration for the Anaconda Copper Mining Co., to break down the Rocky Mountain Mesozoic formations to small units of sedimentation and to trace the principal clastic deposits to their sources in various rising mountain masses along the Cordilleran thrust belt. A series of thickness contour maps of these fans, and of the intervening shale-basin deposits, was made by Billingsley and Lyon in 1922. These maps were based on: (1) U. S. Geological Survey publications; (2) an almost complete collection of oil-well logs as of 1922; and (3) seven months spent in continuous field mapping during which the Mesozoic outcrops were followed continuously from central Montana across Wyoming into northwest Colorado.

The line of thought thus initiated led to the collection of similar data for the later Paleozoic formations, which include thick clastic deposits, obviously of tectonic derivation, in Colorado, Utah, Nevada, etc. The bulletins of the American Association of Petroleum Geologists were found rich in material on the Paleozoic mountain belts in Arkansas and Oklahoma, and their buried extension in Texas and New Mexico. U. S. Geological Survey publications supplied many stratigraphic data. Keith's and Schuchert's papers in bulletins of the Geological Society of America were particularly valuable for Appalachian structure. Field work involving these Paleozoic formations covered the years 1922–1933, when mapping of Utah, Colorado and Arizona mining camps was frequently expanded into the adjoining regions. A paper by Billingsley and Locke on Tectonic Position of Ore Districts in the Rocky Mountain Region [*Trans.* A.I.M.E. (1935) **115,** 59], summarized conclusions as of that date. (Also Geologic Structure of Salt Lake Region, by Billingsley, *Guidebook* 17, Int. Geol. Cong. 1933).

The late pre-Cambrian (Huronian, etc.) scheme of mountain belts was studied after the others. Interest in these early orogenic periods came when work in deepening Rocky Mountain mines began to lead again and again to the basement formation as the place of fundamental motion and structure. More mapping and analysis of the pre-Cambrian is necessary than has been usually given in publications on western mining districts. Too often the basement is lumped as pre-Cambrian schist or gneiss or granite, with the stratigraphy and structure unknown. To secure the necessary knowledge of the basement will be a work of years; but sound progress has been made recently in several areas. Much valuable material has appeared in the publications of the Colorado Scientific Society, for example. With more detailed study has come a new outlook on the processes that have operated in the basement. "Granitization" by replacement, suggested by Quirke and Collins in 1930 to explain the disappearance of the Huronian sediments east of Sudbury, Ontario, seems to be the best explanation of certain features in the West also. (Colorado Front Ranges, Sierra Nevada, Inyo Range, Idaho batholith, Coast Ranges in British Columbia.) Field work by the writers in these areas in 1923–1937 was fortunately supplemented by some months in 1934 and 1937 in the Michigan copper range, where structures, intrusions, and clastic sediments can be correlated in sequences recurring intermittently from Huronian into Paleozoic time.

In 1933 was published, as *Guidebook* 28, Int. Geol. Congress, Philip B. King's Outline of the Structural Geology of the U. S. The writers found in this concurrent study a welcome reinforcement of their own attack on the problem. Believing, however, that the maintenance of their independent synthesis, based on slightly different selections from the literature and on independent field work, will have a certain value, they have in no way utilized King's work in their assembled maps or conclusions. Their principal differences from King's map are three; (1) Billingsley and Locke emphasize more the Huronian and late pre-Cambrian structures; (2) Billingsley and Locke in the Great Basin region use the fold and thrust alignments within the basin ranges rather than the Quaternary normal faults along their edges; (3) Billingsley and Locke have recently begun to emphasize certain tear-fault lines (Lewis and Clark in Montana-Idaho, Walker in Nevada-California; and Anza on the California coast).

The authors wish freely to acknowledge their indebtedness to all workers whose maps, stratigraphic measurements and structural data they have incorporated in their tectonic syntheses. They must also acknowledge the stimulation and broadening of outlook that has come from their too brief readings in European tectonic studies.

Position of Districts*

When the mining districts are placed on a structure map on which the above superimposed and intersecting orogenic elements are emphasized, it appears at once that they are grouped in *clusters of districts* at particular places (Fig. 12). The chief clusters are as follows:

A. In the *roots* of old orogenies, schists, gneisses, drag folds:
    1. Canadian gold districts—earliest orogenies.
    2. Sudbury copper-nickel—late pre-Cambrian, chonolith.

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* Although in the preceding pages we have described only 10 districts, we here place more than 50 on the structure map. Our justification lies in the fact that we are familiar with the additional districts, and have in fact written detailed descriptions of them in a manuscript which is now being prepared for publication. We do not wish to restrict the scope of the grouping by using only the districts that space has permitted us to describe in this paper.

3. Black Hills gold—late pre-Cambrian, drag folds.
4. Jerome copper—late pre-Cambrian, drag fold, intrusives.

B. In the *complex blocks* of superimposed orogenies. These, like the roots, are characterized by the widespread development of schistosity, gneiss and granite. Movement has become adjusted into shear zones in these formations. Parallel structures are dominant:

1. *North Coast Block*
    Juneau gold belt—shear zone on western margin
    Britannia copper—shear zone within complex.
    Bridge River gold—late intrusives within complex.
    Hedley gold—cross thrusts, intrusives, in cover.
2. *Sierra Nevada Block*
    Shasta copper—
    Plumas copper—shear zones within complex.
    Sierra gold—shear zone on western margin.
    Silver Peak gold—shears, thrusts, on eastern margin.

C. In sectors of *early orogenies*, eroded to roots and *rejuvenated* or intersected by later elements:

1. *Michigan Copper*—a "living" structure from Huronian into Cambrian.
2. *Colorado Front Ranges*—late pre-Cambrian plus Tertiary.
    Central City, etc., gold in basement.
    Climax molybdenum in basement.
    Cripple Creek gold in basement.
    Leadville—lead, zinc in cover.
    Aspen—lead, silver in cover.
    Red Cliff—zinc-lead-copper-silver-gold in cover.
3. *Yellowstone Horst*—late pre-Cambrian plus Lewis and Clark tears.
    Pony—gold in basement.
    Jardine—gold, tungsten in basement.
    Chromite belt—chromium in basement.
    Cooke City—copper in cover.
4. *Central Arizona*—late pre-Cambrian plus Tertiary and Walker tears.
    Miami—copper in basement.
    Ray—copper in basement.
    Morenci—copper in basement and cover.
    Globe—copper in cover.
    Superior—copper in cover.
5. *Southern Arizona-Sonora*—Final Paleozoic and Early Cretaceous plus Tertiary.
    Bisbee—copper in cover.
    Cananea—copper in cover.
    Nacozari—copper in cover.
6. *San Juan Mountains*—Final Paleozoic horst plus Tertiary.
    Rico—silver, lead zinc in cover.
    Ouray—silver lead in cover.
    Telluride—gold in cover.

D. At *nodes* on the *later orogenic belts.* The nodes are usually found where the belts are cut by tear faults. Folds and thrusts are sliced by steep faults:

1. *Salt Lake Area*—Cordilleran thrusts plus Uinta tears.
    Park City—lead silver in cover.
    Bingham—lead zinc, in sediments, copper in intrusion.
    Tintic—silver lead in cover, gold in basement.

2. *Boulder Dam Area*—Cordilleran thrusts plus Walker tears.
   - Goodsprings—zinc lead in cover.
   - Pioche—zinc lead in cover, gold silver in basement.
   - Oatman—gold in basement.
3. *Western Nevada*—Great Basin stretching plus Walker tears.
   - Comstock—silver gold in volcanic cover.
   - Tonopah—silver gold in volcanic cover.
   - Goldfield—gold in volcanic cover.
4. *Eastern Nevada*—Early Cretaceous (?) thrusts rejuvenated.
   - Eureka—lead silver in upthrust prong.
   - Ely—copper in crumpled trough.
5. *Montana Gap*—Cordilleran thrusts, Lewis and Clark tears.
   - Butte—copper in intrusion.
   - Phillipsburg—silver in intrusion.
   - Corbin-Wickes—silver in intrusion.
   - Georgetown—gold in sediments.
   - Hecla—silver in sediments.
   - Garnet—gold in sediments.
6. *Coeur d'Alene*—Early Cretaceous (?) thrusts, Lewis and Clark tears.
   - Mullan—copper, zinc, lead.
   - Wallace—silver, lead.
   - Kellogg—silver, lead.
   - Pine Creek—zinc lead.
   - Big Creek—silver.

E. In *foreland uplifts* of early orogenies, mildly rejuvenated.

1. *Tri-State* lead, zinc—Final Paleozoic plus Early Cretaceous.
2. *Southeast Missouri*, lead—Final Paleozoic plus Early Cretaceous.

The importance of the great tear-fault lines is obvious, with Coeur d'Alene, Butte and the Yellowstone districts on the Lewis and Clark line, the Comstock, Tonopah, Goldfield, and most of the Arizona copper districts on Walker-line elements, and Park City, Bingham and Tintic on tear faults marginal to the Uinta Mountains. Since the occurrence of great ore bodies requires the existence of an open channel at precisely the right time, this superiority of the tear faults suggests that of all types of crustal breaks they are the most frequently renewed and reopened. The distribution of historic earthquakes corroborates this conclusion, for Montana earthquakes are on the Lewis and Clark line, Nevada earthquakes on the Walker line, and California earthquakes on the Anza line. Occasional deep-focus earthquakes suggest that these tear lines may be deeply penetrating breaks extending to depths such as 500 km. We suspect that the pattern of tear faults controls the method whereby the earth's rigid crust adapts itself to the equatorial bulge of the spinning globe.

IDEAS ON ORE GENESIS

We find, then, that the ore districts of upper magnitudes are clustered at nodes within the Continental framework, and that these nodes are

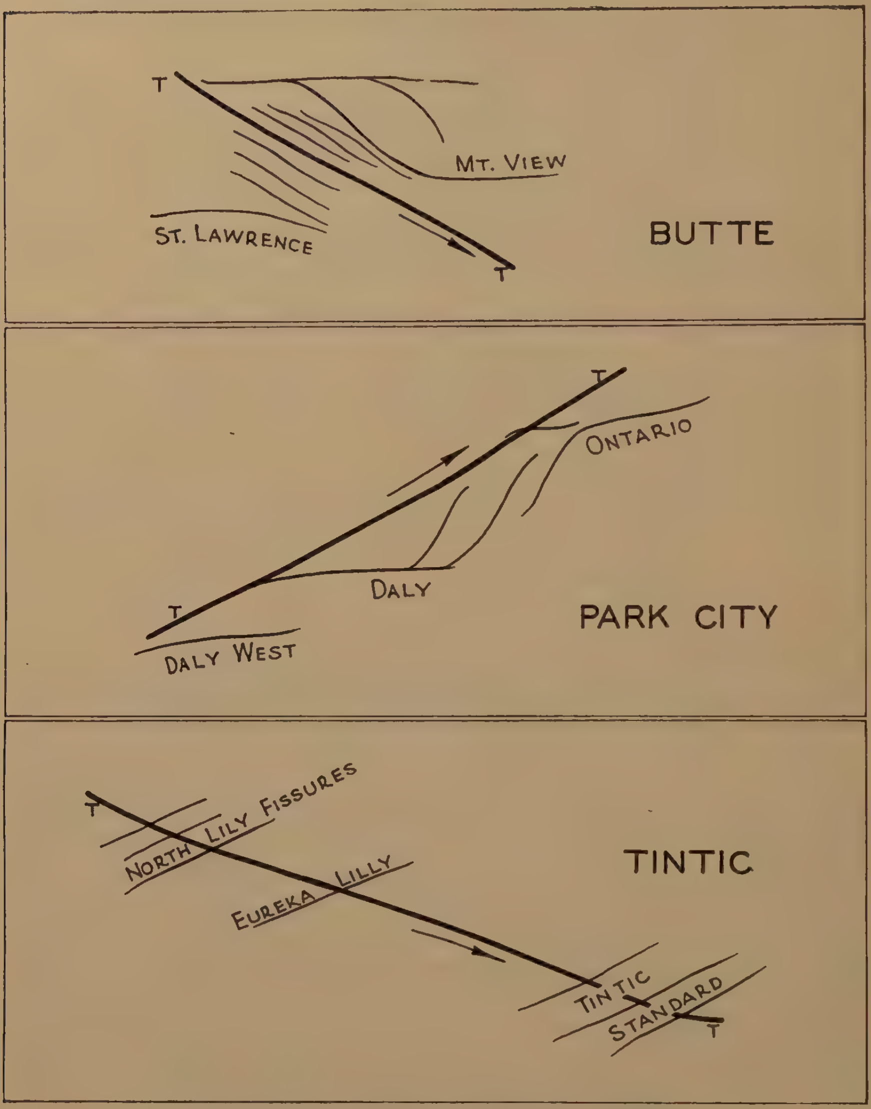

FIG. 14.—TEAR FAULT AND FISSURE PATTERNS.

These sketches are diagrammatic only. They illustrate, however, the patterns formed by the failure of rock under the stresses produced by the motions shown by the arrows.

In Butte the rock is quartz monzonite, which, intruded among Cretaceous shales and volcanics, behaves as a "perched" basement.

In Park City the rock is the Weber formation, a massive Pennsylvanian quartzite 2000 ft. thick, which also forms a perched basement.

In Tintic the rock is Tintic quartzite, over 6000 ft. thick, forming the true pre-Cambrian basement.

determined either by the presence of superimposed orogenic movements or of intersecting lines of successive motion, or of persistent deep-seated breaks. The effect of these factors has invariably been to stiffen the region, to rebreak it and to culminate in widespread heat effects near the surface. The least common denominator is *heat*, moving to the surface through reopened channels in a basement made strong by earlier metamorphism or intrusion, and so competent to carry channels to the depths. Above the basement, the action of the heat is modified by expanding channels in shallow structures and by approach to the surface and to ground water (Fig. 14).

The effects of the heat may cover a wide range. At one extreme is the *melt*, an igneous fluid moving by intrusion and injection. A milder but more widespread effect is produced by *vapors*, gases, etc. This may take the form of granitization, of pegmatitic replacement, of quartz-orthoclase or quartz-sericite or garnet alteration, or merely of recrystallization. Still cooler, below the boiling point, is *hydrothermal* action, "disseminated" ore bodies, vein fillings, ore clusters. At this extreme is the mineral-bearing artesian ground water; and no one can as yet tell to what extent ground water has contributed, with the addition of heat, to the more intense phenomena.

The economic minerals occur in the cooler range of this series. The hot end produces "regional metamorphism" with granite "batholiths" growing at nodes out of schists via gneisses, and with local true melts cutting upward into less altered regions, and possibly reaching the surface as volcanoes. The intermediate stages produce alteration funnels, with vein and ore minerals in their later channels. The cold end ranges from mineral springs depositing metals to cold artesian water. The conventional dogma of igneous hearths seems increasingly artificial and unnecessary in this scheme. The deeper the development of a district the farther such hearths seem to retreat from view. A rush of heat through a channel producing in turn melts, gases and solutions that move toward the surface and there freeze and rebreak, seems for the present an adequate concept of ore genesis, and orogenic motion with breaking seems an adequate cause for the channel and the escape of heat.

DISCUSSION

(*Donald H. McLaughlin presiding*)

P. BILLINGSLEY.—This paper is in the nature of a report to our professional associates on the progress of our geologic mapping of western mines, over a period of years, with certain deductions drawn from the districts mapped regarding the nature and localizing controls of ore deposits of the western type. It was originally presented before the Salt Lake Section about two years ago, but while thus a bit out of date it will still serve this purpose.

The background is one of mapping; underground workings, stopes, surface, cross sections, models, stereograms. Undoubtedly our work has a bias in the direction of field mapping, and our conclusions are weighted accordingly.

The paper is, therefore, fundamentally an expression of the trend of thought induced by the study of mappable geologic features; mainly, of course, structures. In defense of this bias, we can state that in our experience geologic structure has been the one instrument that has worked with reasonable consistency in predicting the behavior and position of ore bodies. Other factors are important—formations, intrusions, alteration, temperature and pressure changes—but all these operate under the control of structure and so follow its guidance.

In brief, we have come to think of the environment of ore deposits as a moving machine, in which formations are caught and deformed, often to the point of failure, with ensuing adjustments that culminate in the lodgment of ore in its specialized traps.

In the first part of the paper are set out some examples of the moving machines, which are mining districts. Goodsprings was chosen because of the simplicity and beauty of its structures; seen in the high visibility of barren hills. The unsymmetrical crumples, riding on thrust faults, found throughout this district are the normal Cordilleran structure. Tintic was chosen because it combines the simple crumple-thrust features with other elements into a complex pattern, which carries an array of exceptionally well-developed ore clusters; Bisbee, because it also parades its ore clusters in a pattern with significant modifications of its own; Leadville, largely because we delighted in utilizing the splendid material made available in Survey publications to show a district with a minimum of folding; Hedley, in order to set this Canadian coast-range district, which has become very closely mapped, alongside the American districts; Ely, because of the close correlation of ore with porphyry chonolith intrusions, in alignment, along a specialized fold trough; Eureka, because this is the district of maximum folding and because of its unique Ruby Hill block; Goldfield, because here for the first time we have found Tertiary volcanics deformed in the true Cordilleran manner.

Even in these very brief flashes of district structures a certain unity can be observed: (1) The moving machine, in these districts, has worked to compress the formations, with forces showing large horizontal components; (2) failure has occurred largely in the form of brecciated overthrust folds and of steep faults with flattish shearing movement (tear faults); (3) these failure belts have served as channels for fluids, which, entering the pattern at various nodal points, have spread under the control of the shallower structures; (4) these fluids comprise, normally, igneous magmas, alteration and ore; (5) the ore, latest in time, occupies the most specialized of the channels and normally is linked into clusters of ore bodies that rise from roots and expand, branch, or spread upward and outward.

The ore-hunting problem in the past decade has broadened to concern itself largely with the search for new clusters within districts, and the significant guides, therefore, are the structures that localize ore clusters. Usually the ore itself does not outcrop, and this type of exploration is a structural problem of the same nature as oil exploration; and, just as with oil we are aided by surface seeps, so with ore we may be aided by such surface phenomena as alteration, slumping and leakages of siliceous sludge.

The next step is an extrapolation, but one that must inevitably be taken. Ore clusters occur at nodes of the district patterns, but what pattern localizes the districts themselves? Where can the ore-hunting geologist look for a new district? The fact that a few tiny outcrops, the accidents of erosion, alone betrayed the presence of Park City, Tintic, and Bisbee must suggest that districts exist unmarked by any outcrop of ore. So we are led into the regional patterns.

Here we are at once confronted with great gaps in knowledge. Very few square miles of territory, beyond the limits of the districts, have been mapped with the detail now common for the districts themselves. But the available regional mapping does show the structures to be composed of the same elements that dominate the district patterns—folds, overturns, overthrusts, tear faults; and the broad position and sequence in time of these deformations can be outlined.

A few of the regions embracing a group of mining districts are sufficiently well known to suggest the comprehensive pattern; such as the Montana Gap, the Salt Lake crossroads, the Colorado mineral belt, and the Miami mineral belt in Arizona. We present sketches of two of these, not in the belief that the final pattern is already determinable, but rather as illustrations of possible lines of attack on the problem. Beyond these few regions, the pattern becomes still more hazy in its outline. Available material for the desired synthesis is of three types:

1. Extensions of major structures outward from districts and other well-mapped-regions.

2. Areal smaller-scale maps, which, while often adequate for the cover formations and in oil and coal fields, usually fail in essential structural detail in the basement rocks.

3. Stratigraphic material, in particular the position in time and place of coarse clastic deposits. These have spread outward from foci of abrupt uplift, which can be visualized as rising, in periods of orogenic activity, here and there above the general level with a varied "firing order" like pistons bobbing up above a motor block when the head is off. Often such clastic fans can be correlated with specific crumples and thrust prongs (as in some basal Tertiary fans in northeastern Utah), and in other cases they may be formed of unique porphyry fragments traceable to specific rising intrusive prongs (as along the Keweenaw peninsula).

Using these three types of data we have assembled a set of tentative orogenic maps, which are grouped into the composite presented in this paper. Obviously this job is in its infancy. It will be of intense interest in the ensuing years to witness the sharpening detail, which has already begun to come from the fine structural mapping of the younger field geologists.

To illustrate our concept of the classification of districts by position in this composite orogenic pattern, we present a tabulation in which about 60 of the larger districts are grouped according to their relationship to orogenic features as now known or inferred. The main groups are: (1) in the roots of old orogenic belts, (2) in complex blocks of superimposed orogenic belts, (3) in rejuvenated early orogenic belts, (4) at nodes of later orogenic belts, (5) in foreland uplifts, mildly rejuvenated. In all the groups the importance of tear faults seems obvious. These structures seem to be a type of crustal failure that most frequently results in the machinery of motion and the transfer of materials from the depths associated with ore districts.

E. Wisser,* San Francisco, Calif.—The comparison of ore districts on the basis of shared structural features, and the relation, in space and time, of such districts to major orogenies are vitally important matters. This paper is a notable contribution to systematic mining geology, not only because of the evidently vast amount of study involved but also because of the breadth of the generalizations reached. The authors advance these hypotheses before all the data are in, and when as yet "the general patterns only can be vaguely seen" (p. 48). This procedure seems entirely proper: additional data needed to test such generalizations are collected with a purpose, and data so collected are commonly of more value than are facts collected at random, whether or not the generalizations eventually turn out to be valid.

I am not competent to discuss the validity of the major generalizations advanced by Billingsley and Locke. I desire to comment, however, on some features of the general treatment and of the terminology.

The authors appear to treat some controversial matters as proved facts. Some geologists may question the existence of a "Walker line" of "tear faults," continental in size and separating Great Basin from Sierra Nevada trends. The Walker-line faults are described as northwesterly steep straight faults with important horizontal displacements in the sense southwestward side northwest. The supposed Walker zone therefore is a duplicate of the San Andreas-Hayward rift zone in California. The latter zone appears to be identical with the "Anza line" of Billingsley and Locke (p. 49), but the failure of the authors to say so adds a needless element of confusion.

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* Consulting Mining Geologist.

The subject of the Walker line is introduced in the discussion of the Goodsprings district. Hewett[1] has published a comprehensive account of the Goodsprings district in which he shows (Plates 1 and 11) a number of northwest faults, more or less steeply dipping. Some of those at the south end of the district appear to correspond to the "Walker line" faults shown in the southern portion of Fig. 2 of the Billingsley and Locke paper. In particular, the Frederickson fault in Hewett's paper (p. 49) seems to be identical with one of the "Walker line" faults. The displacement on this fault may be explained, according to Hewett, by assuming "that it is a transcurrent fault formed during the thrust epoch by the movement of the southwest side northwest, almost horizontally." Hewett thus relates the Frederickson fault to the thrusting; he gives no suggestion that it is a portion of a continental rift zone. Incidentally, it is somewhat disturbing, in comparing Fig. 2 of the Billingsley and Locke paper with Plates 1 and 11 of the Hewett paper, to find the abundant northwest faults in the northern part of the district shown by Hewett entirely omitted by Billingsley and Locke. In a map titled simply "Goodsprings, Nevada—Plan" one expects to find the elements of the whole picture. Among faults of equal magnitude, if one is shown, all the others should be shown likewise, or we do not get the whole picture.

An unfortunate confusing factor is the use by Billingsley and Locke of the term "tear fault" to describe steep faults with horizontal displacements. Hewett does not term the Fredericksburg and similar faults "tear faults," but if he had done so his conception of them would correspond closely to the picture of a tear fault held, I think, by most geologists. Using a reference found at random, Lovering[2] speaks of tear faults as follows:

"The determination of the active and passive blocks of thrust faults is based on the relative movement in the zone where the thrust fault passes into a fold or breaks from a fold along a tear fault. Tear faults commonly strike almost at right angles to the thrust faults, stand almost vertical, and occur between more active and less active regions of folding, where the fault gives way to an overturned fold . . . Thus, tear faults are commonly found in a nearly vertical zone of low-angle shearing, and their steeply dipping walls have moved past each other almost horizontally. They have formed in response to the shearing stresses that caused thrust faulting in the region of active folding and are, therefore, approximately parallel to the direction of the thrust, which is commonly almost at a right angle to the axis of the folds." There can scarcely be any question to the intimate connection of this type of tear faulting with thrusting.

Billingsley and Locke, on the other hand, while their "tear faults" dip steeply and are loci of horizontal movements, distinctly divorce their tear faults from thrusting; or at least their continental zones of tear faulting are no subordinate effects of major thrusting in the sense employed by Lovering (see pp. 13, 16, 23, 57). They say, indeed (p. 57): "We suspect that the pattern of tear faults controls the method whereby the earth's rigid crust adapts itself to the equatorial bulge of the spinning globe."

Matters were confused enough before the publication of the paper under discussion, for the term "tear fracture" had been used as equivalent for tension joint.[3] I plead guilty to this usage myself but think that most geologists would agree that the usage exemplified in the paper by Lovering cited above should be exclusively adopted, for his notion of a tear fault brings "tearing" far more vividly to mind than do the other two uses of the term.

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[1] D. F. Hewett: Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada. U. S. Geol. Survey *Prof. Paper* 162 (1931).

[2] T. S. Lovering: Field Evidence to Distinguish Overthrusting from Underthrusting. *Jnl. of Geol.* (1932) **40**, 651–652.

[3] For example, Robert Balk: Structural Behavior of Igneous Rocks. Geol. Soc. America *Mem.* 5 (1937) 31.

The employment by Billingsley and Locke of the words "basement" and "cover" is also confusing to me. One starts with the natural idea that by basement they mean an underlying complex that behaves as a massive: i.e., it does not deform by folding; and that by cover they mean mainly stratified rocks overlying the basement, and that these rocks do deform by folding under the proper conditions. But they say, for example, that at Tintic zinc-lead veins occur in the cover, gold in the basement. (p. 56). So far as I know, the principal producer of gold ores at Tintic has been the Eureka Standard mine. I visited this mine in 1931 and recall the 1300-ft. level. Both walls of the Eureka Standard fault, along which the ore bodies occur, are Tintic quartzite on that level. The inference appears to be that Billingsley and Locke consider this rock to lie within a basement. But the Tintic quartzite is a member of the Paleozoic sediments, and was folded with them (Fig. 3*c*). One suspects that it is called a "basement" because the Eureka Standard gold deposit has the form of an ordinary tabular vein in contrast to the structure of typical zinc-lead ore bodies in the "cover."

This idea gains some confirmation from the statement regarding Oatman on page 57. The gold quartz veins of Oatman are said to occur in the "basement." The Oatman ore bodies are found in Tertiary extrusives that appear to have been poured out over a basement of massive pre-Cambrian gneiss and granite. (I use basement here in the commonly accepted sense.) In the near-by Katherine district the gold ore bodies of the Katherine mine occur in a vein in the basement (granite here); but the Oatman ore bodies bottom far above the basement and well up in what ordinarily would be termed the cover.

The Oatman and Katherine ores are found in veins, and the vein-fracture pattern is systematic and tolerably regular. In contrast, the copper deposits of Nacozari and Cananea, while they occur largely in Tertiary extrusives entirely comparable to those at Oatman, are mostly pipelike or funnel-like, or have other nontabular forms. On page 56 it is stated that these deposits occur in the cover. One is tempted to advance a definition of the word basement, in the sense used in this paper: a rock, massive or bedded (Tintic) in which ore deposits are found in veins.

Turning to Butte, this definition gains some support. On page 58 the statement is made that the quartz monzonite in which the Butte veins occur "behaves as a perched basement." The systematic fracture pattern at Pachuca is reminiscent, in some ways, of that at Butte. At Pachuca at least 10,000 ft. of massive extrusives, largely flows, rested on a basement of thin-bedded shales and limestones at the time the fractures formed. No sediments ever existed as a cover above these extrusives. Would the fractured Pachuca andesites be termed an "inverted basement"? The same considerations apply, of course, to a very large number of precious-metal vein deposits in Tertiary extrusives.

These thoughts suggest some fault in the perspective of the authors. Of the eight districts they describe in some detail and list on page 13, seven contain replacement deposits in sediments; the ore bodies of the eighth (Goldfield) are far from what are commonly termed vein deposits.

Fifty-eight ore districts are listed on pages 55–57. The nature of three of these I could not check. Of the remaining 55, only 16, or 29 per cent, seem to me analogous to the eight districts described. It seems possible, therefore, that the districts upon which attention is focused in the paper are not sufficiently representative of ore deposition on the North American continent, and that some generalizations derived from study of these districts have been stretched too far in an attempt to apply them generally.

The paper remains none the less a stimulating contribution to our knowledge of the type of ore district chiefly described. It remains to be seen whether a point of view that I think to be somewhat one-sided has invalidated some of the sweeping generalizations advanced. It is to be hoped that the broader conclusions of this paper will be discussed by critics capable of the task.

P. Billingsley (author's reply).—In reply to Mr. Wisser's comments, the authors would say:

1. *Tear faults* had better be called *steep shears,* with the understanding that the movement is predominantly horizontal.
2. *Anza line* is a zone of steep shears, including the San Andreas fault.
3. *Walker line* is also a zone of steep shears. It includes the fault described by Gianella and Callaghan in connection with their description of the earthquake in the Cedar Mountains, Nevada. It also includes the northwest faults in the Goldfield and Goodsprings districts. Long stretches between and beyond these areas remain unmapped, and it is to be hoped that within the near future this important tectonic zone will attract detailed mapping.
4. *Tintic basement:* The Tintic quartzite is at least 6000 ft. thick with no bottom in sight. It is overlain by Ophir shale, 500 ft. thick, above which are the higher Cambrian and Paleozoic formations. Because of flowage in the intervening Ophir member, the overlying formations do not always follow even approximately the folding in the Tintic quartzite. This forms, in fact, a homogeneous deep-seated mass in strong mechanical contrast to the formations above it. Our term "basement" includes this. We have used this term to mean, in respect to mining districts, either the metamorphic complex or such other strong underlying formation as fulfills the same function; i.e., to bring the ore-bearing root channel up to the expanded ore deposits which make in the weaker overlying rocks. We do not, therefore, use "basement" as suggested by Wisser, to mean merely "a rock in which ore deposits are found in veins."

Although our paper, which dealt essentially with regional correlation, does not elaborate the details of ore occurrence in the districts, we may say that we have found, throughout the West, that weak, broken rocks above a strong basement have repeatedly served as traps for bonanza ore masses.

Structural Control of Ore Deposition in Fissure Veins

By H. E. McKinstry,* Member A.I.M.E.

(New York Meeting, February 1940)

Movement on a fracture of irregular shape can cause local widening of the fissure and thereby offer freer channelways for circulation of ore-depositing solutions. This influence. coupled with large areas of wall rock available for reacting with ore solutions in brecciated and shattered ground can account for locally active deposition of metals and the resulting ore shoots. Such irregularities in the fracture system may be caused by local variations in the strength of rocks and by pre-existing lines of weakness, especially if these stand at favorable angles to certain components of the fracturing stress. Therefore correct interpretation of the mechanics of fracturing should permit deductions as to structurally favorable places on unexplored portions of the vein system.

Introduction

It has long been recognized that movement on a curved or irregular fault surface is capable of separating the walls in certain portions of the fault, but until very recent years the importance of this mechanism as a factor in localizing ore shoots has escaped proper recognition. A short time ago W. H. Newhouse[1] presented a careful analytical study of displacements and their corresponding open spaces.

For reasons that will be discussed later, it frequently happens that portions of the vein which are favorably oriented are not merely wider but also richer than the average. In many cases the widening with its accompanying richness coincides with very minor changes in the dip or strike of the vein, irregularities that commonly escape notice unless the vein is mapped in detail and a careful geometrical analysis made.

While the relationship between the width of the vein and the changes in dip or strike has been recognized as a matter of observation, the irregularities have been accepted as more or less the result of accident. There has been very little effort except in isolated cases to find out the *causes* of these changes in dip or strike. Yet it is clear that if the causes can be recognized and expressed in terms of geologic structure the geologist will know where to look for repetitions of these favorable conditions either on extensions of the same vein or on adjoining veins.

Any lack of understanding of the causes is due to the limitations of our ability to interpret our observations and not to the sheer capriciousness of

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[1] References are at the end of the paper.

nature. Unquestionably fractures come into existence as a response of rocks to stress, therefore one line of attack on the problem is to study, from a mathematical and experimental standpoint, the behavior of materials under stress. Another line of attack is from the field side—a study of the patterns of fractures in districts whose structural history can be safely inferred. We still have a great deal to learn about such matters and perhaps it is rash at the present stage to attempt any correlation between the theoretical considerations and the field facts, but I am convinced that an effort in this direction is worth making, and that the goal will eventually be achieved by a convergence of the two lines of investigation. Meanwhile the effort to analyze field facts leads to generalizations that can be put to practical use in the search for ore even though the precise explanation may still be in doubt.

Mechanical Principles

When rocks and similar materials are loaded beyond certain limits, they either fail by fracturing or yield by "flow." Since flow does not in itself produce definite fissures, we are here concerned chiefly with failure by fracture. Whether or not a rock will fail by fracture and, if so, what positions and shapes the fractures will assume, cannot at present be predicted by any general rule, since there is as yet no wholly satisfactory theory of rupture. Yet experiment and observation indicate that there is at least some approximate relationship between the planes of failure and the orientation of stress in the material at the time of rupture.

The following paragraphs are offered as a brief review of the mechanical principles bearing on the failure of rocks under stress, and are intended at the same time to define the sense in which engineering and structural terms are used in this paper. This seems advisable because geologists (myself included) have often used such words as "stress," "shears" and "pressure" in an ambiguous manner.

Stress may be defined as the internal force exerted by one part of a body upon the adjoining part.[2] The term, as ordinarily used, means *unit stress;* i.e., the internal force per unit area.

Orientation of Stresses.—The stress that exists at any point within a stressed body has components acting on each one of the infinite number of planes that may be imagined as passing through the point. On any plane the stress may be represented as the resultant of components acting normally and parallel to that plane. Of all imaginable planes it is possible to select three, mutually at right angles to each other, in which the parallel component of stress (i.e., shear stress) is zero. This preliminary discussion will be limited to the special case in which there is one plane in which not only shear stress is zero but normal stress is also zero. A test block loaded on one or two sides but not on the third side would comply with this condition.

Critical Planes.—In the special case discussed here, there are four planes on which the stresses have critical values. Two of these, at right angles to each other, are those on which *normal stress* reaches its maximum and minimum values, respectively (i.e., principal planes). On these planes shear stress is zero; the normal stress may be either tensile or compressional. In physics and engineering it is customary to denote tensile stresses by a positive sign and compressive stresses by a negative sign. Using this convention, the plane in which normal stress has a maximum algebraic value is called the plane of maximum normal stress; the plane on which it has the minimum algebraic value is called the plane of minimum normal stress. Thus if both principal stresses are tensional the plane in which stress is numerically larger is the plane of maximum normal stress; if both are compressional the plane in which stress is numerically smaller (but in this case negative in sign) is the plane of maximum normal stress.

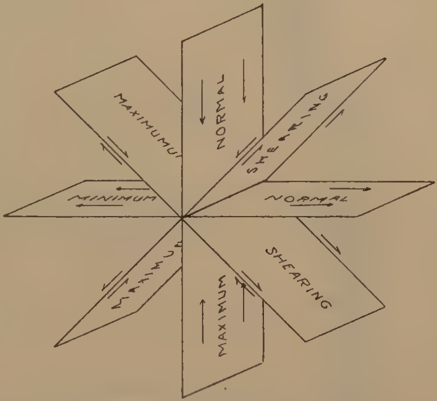

FIG. 1.—PLANES OF CRITICAL STRESS VALUE THROUGH A POINT.

The other two critical planes, are those in which shear stress reaches its maximum, and these planes also are at right angles to each other.

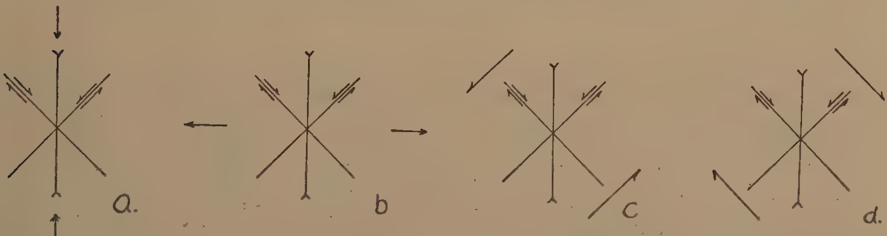

FIG. 2.—ORIENTATION OF PLANES OF MAXIMUM STRESS WITH VARIOUS TYPES OF EXTERNAL FORCE: (*a*) COMPRESSION, (*b*) TENSION, (*c, d*) SHEAR.
Note that orientation of planes of maximum stress is identical in each case. Trace of plane of algebraically maximum normal stress is indicated by line ending in carats. Actual stress on this plane may be positive (tensile) or negative (compressile).

The four planes (two of maximum shear stress, one of maximum normal stress and one of minimum normal stress) intersect in a single line and form eight dihedral angles of 45° each (Fig. 1). In most of the illustrations accompanying this article (e.g., Fig. 2) the traces of these planes on the plane of the paper are shown as a figure resembling a cross superimposed on an x, the plane of maximum normal stress being indicated by the tail of an arrow without implication as to whether it represents maximum tension or minimum compression. The stress planes are to be imagined as extending into space normal to the plane of the paper.

The stress at any point is equal to the resultant at the point of the forces that act on the body of rock. While external stress may be applied in a variety of ways, the four critical planes of stress at any point always stand at angles of 45° with each other (Fig. 2).

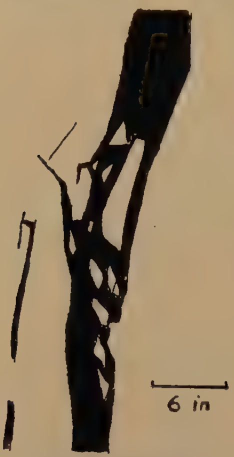

Fig. 3.—Vein (calcite-smaltite) in diabase, O'Brien mine, Cobalt, Ontario. (*After W. L. Whitehead.*)

While the foregoing discussion has been limited for simplicity to the case in which stress exists in only two dimensions, it may be extended to the more general case of stress in all three dimensions without altering the position of the planes of critical stress, provided the resultant of the stress in the third dimension (in this instance acting normal to the plane of the paper) has a value between those of the two principal planes of the diagram.

Uniform and Nonuniform Stress.—It should be repeated that the assemblage of planes just described applies, in the most general case, only to a single point within the body and the planes extend only an infinitesimal distance from the point. In the special case of uniform stress (and this is the case that is commonly in mind when such matters are considered) the assemblages of planes about each point have a common orientation, therefore a single diagram serves to describe the stress throughout the body. But even the more general case (nonuniform stress) can be depicted if we imagine the diagram as varying in orientation from point to point in the material; in the latter case the diagram (the assemblage of critical planes), while changing its position, does so as an assemblage. At any one point the planes all stand at 45° to each other. This is like the swing of a compass dial in response to changes in an electric field without any alteration in the *relative* positions of the points on the dial.

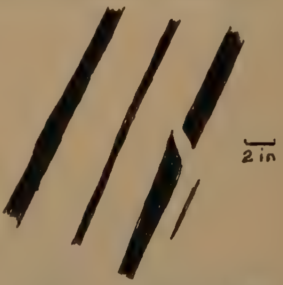

Fig. 4.—Quartz-filled "tension cracks" in granite. Siscoe, Quebec.

No specialized kind of stress is produced by torsional forces, for torsion is merely a special case of nonuniform distribution of stress; the orientation of the principal planes varies systematically from point to point in the third dimension, but at any point it can be analyzed into normal and shearing components.[3]*

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* While some fracture systems may be correctly attributable to torsional forces, it is possible that geologists sometimes invoke torsion without adequate evidence, perhaps through mental confusion between forces producing torsion and those merely producing shearing.

Nor is any special kind of stress produced by "rotational" forces, for the effects of such forces at any instant can be completely described by their normal and shear components—but in this case the orientation of the principal planes of stress changes progressively with time as deformation continues. (Or, in other words, the position of the material with respect to the principal planes changes progressively.)

Instead of the foregoing explanation, the behavior of loaded materials might have been described in terms of the conventional ellipsoid of strain,* for in isotropic materials the principal planes of the ellipsoid correspond to the planes of principal (normal) stress. However, the modern tendency is to relate shear failure to stress rather than to strain[6] and, furthermore, it seems a little simpler to focus attention on planes than on axes.

Isotropic and Nonisotropic Materials.—The principles of stress described above apply to all elastic materials, whether isotropic or nonisotropic.† In nonisotropic materials, however, the strains resulting from a given state of stress are determined by constants, which vary in different directions within the material. The factors governing failure are even less clear than in isotropic materials, hence no attempt will be made to include nonisotropic materials in the ensuing discussion of fracturing. Reference to the problem will appear in a later section (p. 75).

Relation of Fractures to Stress.—Experiment indicates that brittle materials fail by fracture in one of two ways or by a combination of the two: (1) by separating along planes that are approximately parallel to the plane of maximum *normal* stress; (2) by slipping along planes that are approximately parallel to the plane of maximum *shearing* stress.

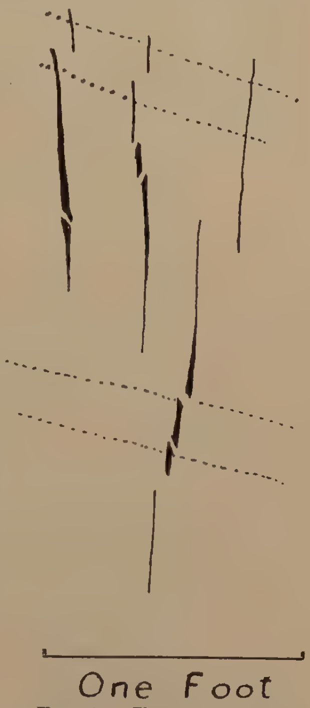

FIG. 5.—TENSION CRACKS FILLED WITH CALCITE IN SLATE.

Note bridging "semi-inclusions." Plan, sketch, East Bangor, Pa.

Very commonly the surface of rupture alternates between these two directions, changing its course at intervals that may vary from large to microscopic.[8]

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* The strain ellipsoid, despite recent criticisms, remains a valid and convenient device for depicting the state of strain at any point. It does not in itself constitute a theory of rupture,[4,5] nor does the assemblage of planes here described pretend to do so.

† Nonisotropic (allotropic) materials are those in which the elastic constants vary with direction (p. 314 of ref. 6).

Experiments indicate further that in the absence of confining pressure brittle materials behave elastically, or nearly so, up to the time of failure. Therefore it may be expected that under these conditions fracture will take place along planes in which the stress first exceeds the ultimate strength.*

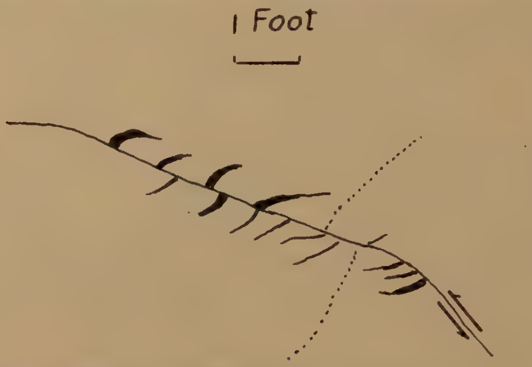

FIG. 6.—TENSION GASHES ALONG A FAULT IN SLATE. Displacement is shown by the bedding plane (dotted). No. 8 level, Morning Star mine, Woods Point, Victoria.

But under other conditions rocks may suffer notable permanent deformation by "flow" before rupture.† In such cases rupture occurs at some stage after the elastic limit has been exceeded, hence after materials have ceased to behave according to the laws of elastic stress. Nevertheless laboratory experiment and geological observation both indicate that the position and shape of the surface of rupture bears at least a qualitative relationship to the orientation of stress that existed in the material while it was still within the elastic limit.

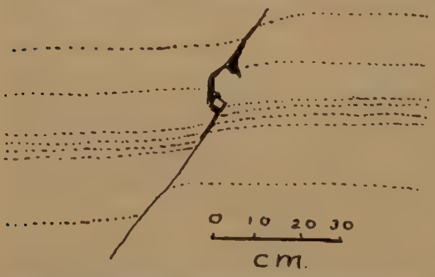

FIG. 7.—TENSION OPENINGS ALONG FAULT IN LIMESTONE. (*After E. Seidl.*)

Shears.—Experiment shows that when failure takes place predominantly by shear the surface of failure does not strictly correspond to the plane of maximum shear *stress*. Thus, instead of making an angle of 45° with the plane of maximum normal stress, it usually makes an angle of a few degrees less than 45°

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* "Ultimate strength" is a convenient but inaccurate term, as the differential stress required to produce rupture in any given material varies under different conditions. It is modified, for example, by confining pressure, temperature, presence of a solvent, and duration of the stress.[7,8]

† Griggs' experiments with limestone and alabaster indicate that flow by recrystallization is promoted by presence of a small amount of water or other solvent. The deformation proceeds slowly and may culminate in rupture after a lapse of time without increase in load.[7]

with this plane. The actual angle, which varies for different types of material, is called the *shearing angle*. According to the Mohr theory[9] shearing takes place on planes in which there is an optimum combination of shearing and normal stress, and usually normal stress is a little greater (algebraically) than on the plane of maximum shearing stress.

"Tension Fractures."—When brittle materials are loaded by applying a tensile force, they usually fail along surfaces that are normal to the axis of applied tension; i.e., along surfaces that approximate the plane of maximum normal stress. Fractures having this attitude are commonly called "tension fractures" or "tension cracks." That such fractures will form in rocks that have suffered tensile load is to be expected. That they will form in rocks subjected to pure shear is also to be expected, for in pure shear one of the principal normal stresses is positive in sign. But that they can form even in materials that have been loaded by the application of compressive forces may be surprising; nevertheless, it has repeatedly been accomplished experimentally. For example, Griggs[8] finds that when cylinders and prisms of limestone are axially compressed, "tension fractures" develop approximately parallel to the axis of compression; i.e., again parallel to the plane of maximum normal stress. He states that confining pressure lessens the tendency to form tension cracks but that they develop to some extent in specimens even at 10,000 atmospheres confining pressure, corresponding to a terrestrial depth of about 20 miles. I have observed fractures having the characteristics of tension cracks at depths of over 3000 ft. in the Porcupine district and at a depth of over 6000 ft. on the Rand. At the time they were formed, they must have been many thousands of feet deeper than that.

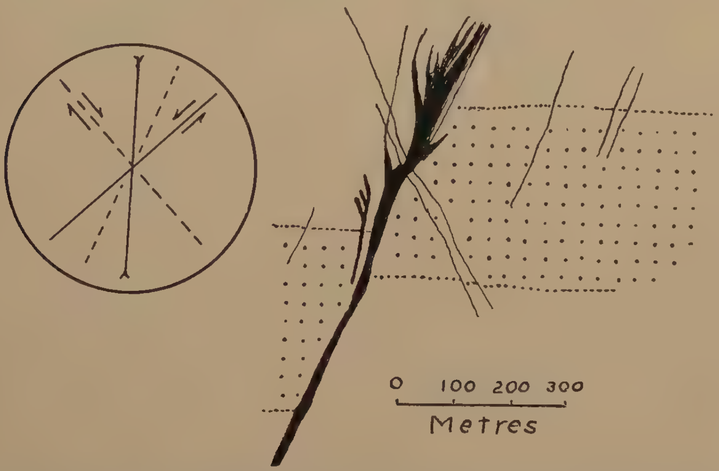

FIG. 8.—CROSS SECTION OF SAN RAFAEL VEIN, EL ORO, MEXICO. Andesite layer in slate displaced by normal fault. After Teodoro Flores: Inst. Geol. Mex., *Bol.* 37.

"Tension fractures" may develop alone or in association with one or both sets of shears. When shears and tension fractures are formed together they often intersect at sharp angles, but in some instances shears may curve into tension fractures. Ruptures have been observed also in which the walls have been separated by movement having both normal and parallel components.

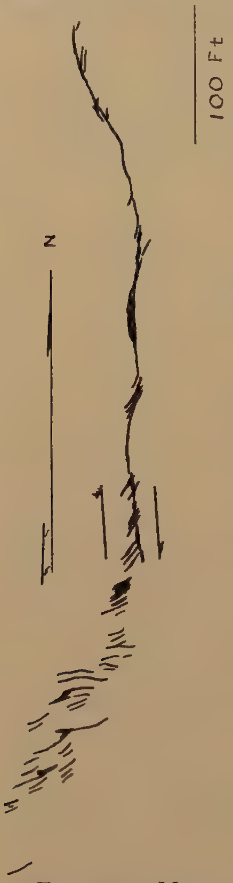

Fig. 9.—Main vein Zone on ninth level, Siscoe, Quebec.
From geologic maps by James, Gillanders and others.

Characteristics of Fractures Formed by Shear and by Tension.*—It is not always easy and sometimes not possible to distinguish fractures developed by shear from those developed by tension. Often, however, inferences may be drawn from certain characteristics. A shear may consist of a single plane of slip but very commonly a group of closely spaced subparallel shears constitutes a shear zone. Often the slivers between the individual planes of slip are partly or completely replaced by gangue, preserving only remnants or residual streaks. This produces a type of "ribbon" vein,[11] which can easily be misinterpreted as the result of either post-vein shearing or repeated reopening ("book structure"). The slivers and planes of premineral slip in such a vein are often represented by streaks and bands of pyrite or other sulphide. Fractures formed by shear are sometimes marked by slickensides, which may be preserved as "fossil slickensides" in the replacing gangue. Shear fractures are commonly though not always marked by gouge.

Fractures formed by tension are often, though not necessarily, gash-like, short and fat. That normal movement separated the walls is often to be inferred from the fact that the walls would fit together if the filling were removed. Characteristically there are angular inclusions (Fig. 3) or the replaced "ghosts" of them; in some instances the inclusions have been displaced and jumbled, in others they could be fitted together again.[12] Not uncommonly partly detached slabs bridge diagonally across the vein from one wall to the other (Fig. 4). Tension fractures do not always come singly; they may be parallel and closely spaced, forming sheeted ground (readily mistaken for a shear zone), or they may be arranged en echelon, either along a shear (Fig. 6) or forming the continuation of a shear that dies out (*fiederklüfte*, or "horsetails," Fig. 9).

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* Visible planes of rupture are here called fractures, regardless of whether they have originated through shearing or normal stress. A group of fractures having approximately the same attitude (i.e., approximately parallel to each other) is called a *set* of fractures. Two or more intersecting sets constitute a *system*, whether formed as a single episode or as a succession of unrelated episodes.[10]

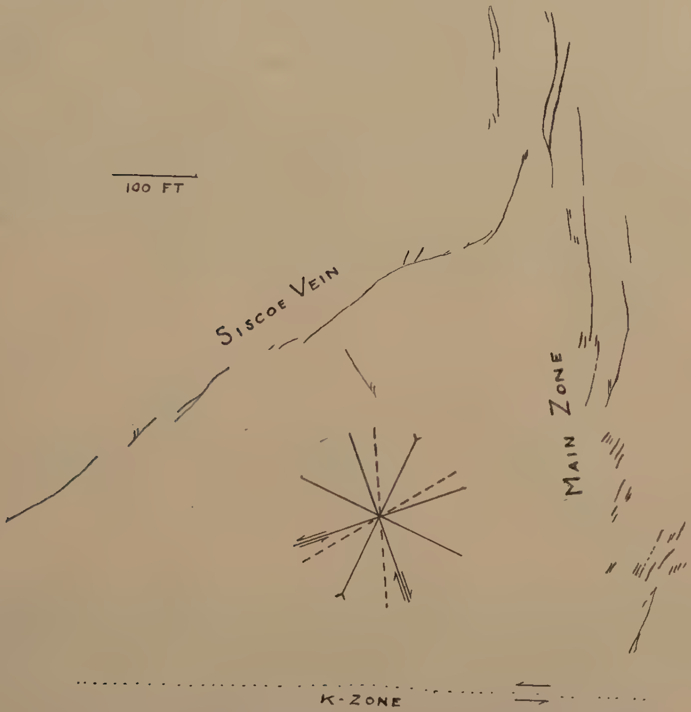

Fig. 10.—Main and Siscoe vein system at Siscoe, Quebec. Section on an inclined plane dipping N. 67 W. at 35°. Data from mine maps by James, Gillanders and others.

The Ideal Fracture Pattern

An idealized pattern of fractures might consist of two sets of shears with a set of tension fractures bisecting the angle between them. Such a pattern, needless to say, is rarely if ever found in natural examples, yet often it is roughly approximated, particularly in vein systems in homogeneous* rocks like granite and porphyry (Fig. 10). The sets of fractures composing the pattern are not ordinarily developed with equal prominence; any one or even two of the sets may be subordinate or absent. The fractures forming the pattern give a clue from their nature and attitude to the orientation of the stresses that caused them. The stresses themselves are no longer present, of course; their former orientation must be determined purely by inference. The inference may not be strictly accurate as to angle but if it is consistent with the observable facts it furnishes a useful working hypothesis. As a basis for such an inference, it is not essential that all of the ideal fractures be present. It is necessary only to identify one plane of shear and either (1) the direction of movement along it, or (2) the fractures which represent the plane of maximum normal stress. From these observations the rest of the diagram can be reconstructed.

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* Being composed of grains or layers, no rock is truly homogeneous, but unless layering is conspicuous, rocks are, generally speaking, statistically homogeneous if the dimensions under consideration are large compared with the grain size.

It must, of course, be remembered that, since the assemblage of stress planes may have any orientation, neither a horizontal plan nor a vertical section will in the general case afford an undistorted picture. The true cross section appears only in the projection on a plane normal to all of the planes of maximum stress; i.e., perpendicular to the line of their common intersection. Wisser[13] has prepared an interesting series of sketches showing the great variation in the apparent angle of intersection of two planes, occasioned by various pitches of the line of intersection. The extreme case is that of no pitch (i.e., angle of pitch equal to zero), in which the two intersecting planes appear parallel in plan view.

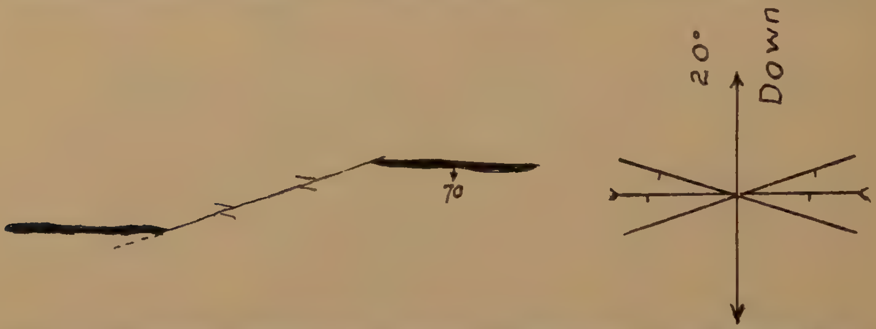

FIG. 11.—SCHEME OF VEIN SYSTEM, BALATOC, PHILIPPINES. (*After Andrew Leith.*) Diagram at right shows orientation of stress planes. (This is a horizontal section. A section truly normal to the common intersection of the stress planes would be inclined 20° to the plane of the paper.)

DEPARTURES FROM THE IDEAL FRACTURE PATTERN

It has been shown that in nonuniform stress the orientation of the stress diagram varies from point to point within the material. The traces of the critical planes, which, for any one point, are of infinitesimal length, combine, when integrated throughout the body, to form curves. Hence bodies of rock subjected to nonuniform stress might be expected to fail along either curved or irregular surfaces. Thus nonuniform stress can be one of the causes of irregularly shaped fractures. It may be occasioned either by action of external forces on a body of material having an irregular shape or by the action of forces which vary locally in direction or intensity.

The pattern of fractures may also be expected to depart from the ideal if the material is nonisotropic (see p. 69). Slates and schists, for example, while they may probably be regarded as statistically homogeneous, possess greater strength in certain directions than in others. Therefore failure would be governed only in part by the stress distribution; it must be governed in some degree by the directions of weakness. To determine the manner in which materials of this sort fail requires further experimental work but it may safely be assumed that fractures in them will take directions different from those in isotropic materials and will vary in some manner in accordance with local variations in the direction of the cleavage.

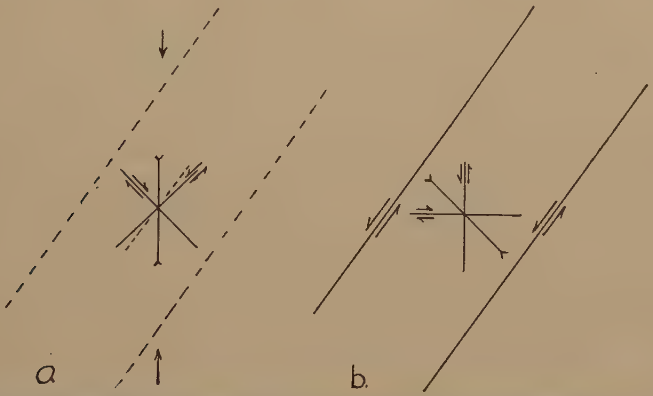

FIG. 12.—ORIENTATION OF STRESS IN SLICE BETWEEN TWO MOVING SHEARS: (*a*) BEFORE RUPTURE, (*b*) DURING MOVEMENT.

Parallel component of external force is used partly in accelerating motion of material and partly in overcoming friction on fault plane. Only latter portion is transmitted across fault plane; this is naturally less than shearing stress at moment of failure. Normal component is transmitted across fault plane in toto.

In addition to these causes of irregularity, any pre-existing surfaces of weakness within the rock-mass will, when once established, become preferred places for subsequent failure. Motion along such planes upsets the equilibrium of forces and the rock no longer behaves as a single elastic body. If fractures continue to form they will have a different orientation from that which would be expected from the original state of stress (Fig. 12).

Some of these factors will be discussed further in the following sections.

Deformation Continued after Initial Failure

Failure in response to internal stresses establishes incipient planes of slipping and opening but it seems likely that openings of appreciable size can be produced only by continued deformation. A fracture system may thus be regarded as the result of a progressive process, no matter whether it was completed in a few minutes or a few centuries. Once the planes of failure are established, they become preferred surfaces of movement which may open certain portions of the fracture system and keep others closed.

Thus, although separation of the walls would theoretically be expected chiefly on planes of maximum normal stress and although shears, if ideally plane surfaces, would not be *opened* at all, the continuation of movement actually sets up wedging and bridging effects, which may cause separation of the walls of shears or even induce tangential movement of the walls of tension fractures. Nevertheless, it is to be expected that when fractures have been opened by continued action of the same forces that caused them to form in the first place, the pattern of veins and the places of opening will bear a symmetrical relationship to the original orientation of stress, and it follows that the fractures, whether originally shears or tension openings, will intersect in lines parallel to the common intersection of the planes of principal stress. Hence, providing conditions do not vary drastically in the third dimension, the intersections of the fractures in any one system should all have the same pitch, and in this case the intersections of minor fractures will serve as clues to the attitudes of major ones. A vein that changes its path from a shear to a tension fracture (or to a plane on which there have been components of both shearing and normal stress) should be expected to do so along a line having this same pitch. Where fractures have been opened, the openings should be wider along the planes that are more nearly parallel to the plane of maximum normal stress.

Ability to recognize the orientation of the planes of principal stress in a vein system of this origin should lead therefore to certain inferences of practical value, and in the absence of complicating factors should indicate: (1) the pitch of vein intersections and therefore the pitch of ore shoots where they are localized by vein intersections; (2) the pitch of a line on which a vein changes its direction or attitude; (3) the attitude of the portions of the vein that are likely to be widest; (4) the pitch of ore shoots that are localized by this widening.

Failure on Surfaces of Weakness

Loci of weakness may consist of any one of a number of features, such as: (1) pre-existing fractures (faults or joints); (2) rock contacts, e.g., margins of intrusives; (3) bedding planes. As the external force is applied and internal stresses increase, the surfaces of failure will be those in which the stress first exceeds the strength.* Surfaces along which the rock is weakest will be favored places of failure. This does not mean that the rock necessarily will break along its weakest plane, for the stress may be so oriented that the strength in this plane, even though low, will still exceed the component of stress that is acting on it. Another plane on which the strength is greater may instead be the plane of failure because the stress is also greater. The surfaces of failure and therefore the pattern of fractures will be a compromise between the pattern that would form in continuous rock and the pattern of weak surfaces.

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* Strength as here used is an inclusive and admittedly vague term. See footnote to page 70.

Pre-existing Fractures.—Faults or joints of an older system may serve as planes of weakness to localize movement during a new period of deformation (Fig. 13). This condition is somewhat similar to that described above, in which fractures are opened by a continuation of the same forces that inaugurated them. The two cases are often difficult to distinguish and, in fact, the distinction may be academic. However, where there have been two separate and unrelated periods of deformation, the vein system may be expected to depart farther from the "ideal fracture pattern" and to show a greater diversity in the attitudes of individual veins than where the fractures have been formed and opened by a single set of external forces.

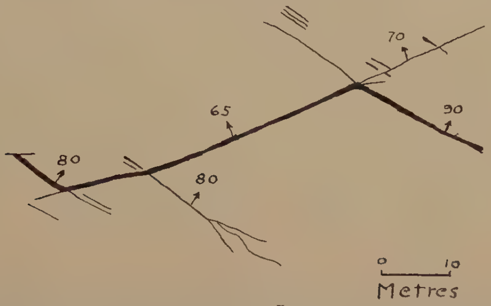

FIG. 13.—PLAN OF PORTION OF VEIN SYSTEM AT LLALLAGUA, BOLIVIA. (*After Turneur.*) Stoped portion shown by heavy line. Pattern suggests opening guided by a pre-existing system of joints or fractures.

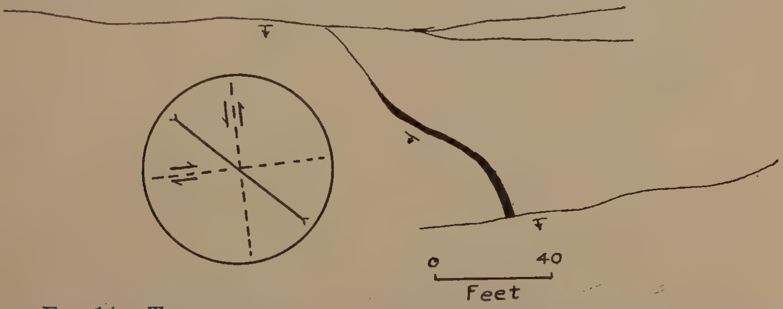

FIG. 14.—TENSION FRACTURE FORMING LINK BETWEEN TWO SHEARS. Viking mine, Norseman, W. A. Plan. Actually stress diagram should be tilted so that plane of maximum normal stress dips toward lower left. Data from mapping by Conolly and Campbell.

A common type of fracture pattern consists of shears or other surfaces of weakness arranged en echelon and connected by oblique linking veins. Sometimes the links have the earmarks of tension openings; sometimes such criteria are absent or unrecognizable and movement on the links may have had a strong tangential component.

A simple experiment shows that if two planes of weakness lie en echelon, application of shearing stress in the appropriate direction produces failure along a diagonal tension fracture. This, I believe, explains the structure of the vein system at Norseman, W. A., where steep shears are joined by flatter links having the characteristics of tension openings (Fig. 14). The controlling planes of weakness or "guiding shears" that show en echelon arrangement on a particular section may approach each other in the third dimension and become a single continuous shear. Where this happens the ore shoot is likely to die out. Some lenslike ore shoots, as in the Coeur d'Alene district, are associated with a local swing in strike, which disappears on deeper levels and also near the surface; the resulting ore shoot, when viewed in longitudinal section, has the shape of a tobacco leaf.

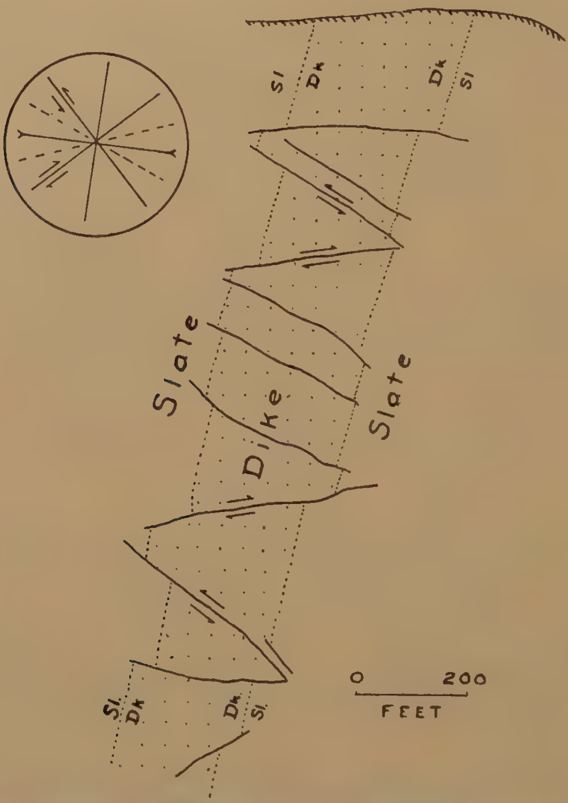

FIG. 15.—VEINS FORMED BY CONJUGATE SYSTEM OF REVERSE FAULTS CUTTING DIORITE DIKE IN SLATE. (*After Stone and Broadhurst.*) Transverse section. Wood's Point, Victoria.

Bedding Planes.—Bedding planes often serve as loci of weakness. "Bedding-plane faults" and their relation to ore bodies have been described in an excellent analysis by Behre.[14] As a comment on his discussion of saddle reefs, it may be pertinent to note that Behre's information was based on the published descriptions available at the time; hence it was only natural that he accepted the classic conception of the structure of saddle reefs. Recent studies[15,16] show that the Bendigo reefs, with few or no exceptions, fail to conform to Behre's saddle-reef type but more closely resemble his steep reverse type. Each ore body is localized by a fault, which takes advantage of the weakness provided by a bedding plane along the limb of a fold, but above the crest each fault continues, flattening slightly and crossing the bedding. Evidence has been presented[17] to show that the faults and their accompanying ore bodies were developed not as a part of the folding but as a later episode, and that the rocks at that stage were brittle rather than plastic because erosion had, by that time, removed part of the overlying load.

If a folded bedding plane constitutes a surface of weakness, the parts of it that are favorably oriented may serve as places of movement and opening; stresses that cannot be relieved by movement on the bedding plane will produce new fractures in the rock.

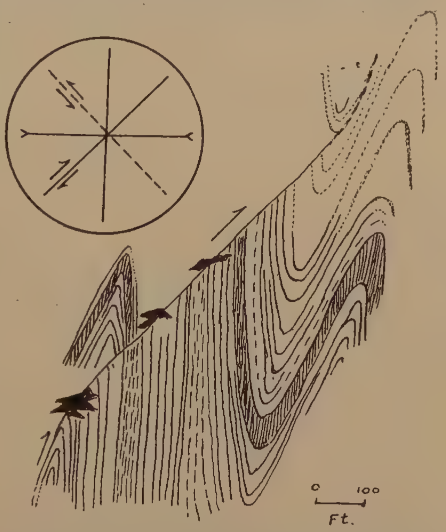

Fig. 16.—Fault following bedding on inclined limb, crossing bedding on vertical limb of fold. (*After W. Baragwanath.*)
Britannia United Mine, Ballarat, Vic. Cross section looking north.

This principle is illustrated by the reefs at Ballarat, Vic. (Fig. 16). The plane of maximum normal stress was evidently horizontal, so the shearing component in the horizontal, and also in the vertical, plane was zero. Where the beds were not vertical but inclined (as in the west limbs of the anticlines where the dip is 60° to 70°) the shearing component was relieved by slip along the bedding. But in the east limbs, where the bedding was vertical, the shearing component could be relieved only by dip faults. Thus the "leather jackets" (faults) develop in the east limbs of the anticlines where the beds are vertical.

The conditions in one (and perhaps several) of the mines on the Mother Lode appear to have been similar. In the Original Amador the main shearing is localized by a contact, but a great, flat quartz lode forms a link connecting the main shear with another shear in the hanging wall. Fig. 17 embodies the suggestion that the hanging-wall shear may be localized by the same contact on the flank of a tight fold.

Dislocation along a zone or surface that cuts the bedding planes may be facilitated by local slipping along the bedding, if the direction of movement is normal to the trace of the bedding. In fact, the dislocation may be accommodated by buckling or flexing without continuous fracturing. But if the direction of movement is parallel to the trace of the bedding it cannot be accommodated in this manner and must express itself in fracturing* (Fig. 18). Thus, in the Interstate mine, Idaho, a steep zone on which displacement was horizontal forms ore shoots where the bedding is flat but causes little or no fracturing and no ore shoots where the bedding is steep.[18]

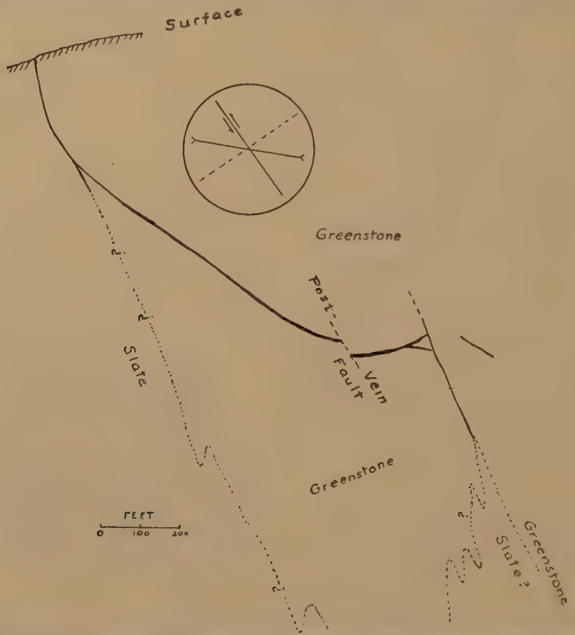

FIG. 17.—FLAT VEIN LINKING ACROSS BETWEEN STEEP FAULT FISSURES. ORIGINAL AMADOR MINE, CALIFORNIA.

Cross section looking north (partly diagrammatic). Suggested interpretation: "Flat" vein is "tension fracture" where it joins eastern fault fissure. Toward West it swings into "shear direction" and joins western fault fissure. Eastern and western fault fissure may represent slipping on contact where fold limbs dip eastward.

Deflection of Fractures in Contrasting Material

It is commonly observed that a fracture changes its direction when passing through a layer of material that is different in physical properties from the surrounding rock (Fig. 19). Two explanations for this behavior have been suggested.

1. The "shearing angle" (see p. 71) varies in different materials, hence a shear would be expected to vary in attitude even though the planes of

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* Under certain conditions it can produce a series of domes and basins en echelon.[3]

maximum shearing *stress* remained constant. Knopf[19] aptly draws a parallel to the refraction of a beam of light and estimates the "index of refraction" for certain types of rock on the Mother Lode.

2. The statement is frequently made that fractures where crossing a strong or hard layer tend to assume a direction at right angles to its contacts, thus taking the shortest course through it. Certainly such shapes are not unusual and the explanation is plausible, but whether a fracture would take this course even though the influence of the "shearing angle" would tend to deflect it in the opposite direction is a matter that requires further experimental and mathematical investigation.

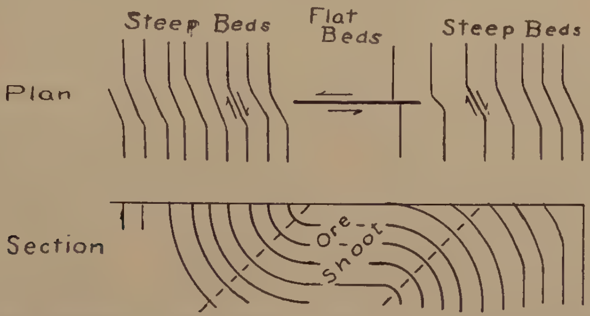

Fig. 18.—Displacement taking form of fracture in flat portion of fold changing into flexure in steeper limbs. Oreshoot confined to fracture. Idealized sketch but simulating conditions in Interstate mine, Idaho.

Whatever the reason, fractures are commonly more or less deflected on passing through layers of contrasting material. With continued movement the fracture (vein) is opened or tightened depending on the direction of slip and the direction of the deflection. Fig. 20 shows the possible variations and the positions of the potential openings.

The layer that causes the deflection may be an igneous dike or sill or it may be a sedimentary bed or formation. Deflections localizing ore shoots may be repeated in some particular formation with such consistency as to brand it as "favorable" and an adjoining formation as "unfavorable." If the true cause is not recognized, it is customary to explain the condition by invoking some obscure chemical influence.* Failing this, the investigator seeks some consistent physical property of the "favorable" bed. From what has been said it will be recognized that the "favorability" of a bed under these conditions depends as much on the physical characteristics of the adjoining beds as on those of the bed in question; in other words, that material A may be "favorable" when it is sandwiched between beds of material B and "unfavorable" when it is bounded by beds of material C. Or that it may be "unfavorable" if the bed lies in a different position with respect to the movement on the vein. These considerations should constitute a sufficient warning against dismissing any bed or formation as inherently "unfavorable," or, on the other hand, banking too strongly on its being "favorable" unless the real cause is understood.

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* I should be the last to deny the importance of the chemical influence of wall rock on ore deposition. I believe, however, that the purely physical factor is too often overlooked.

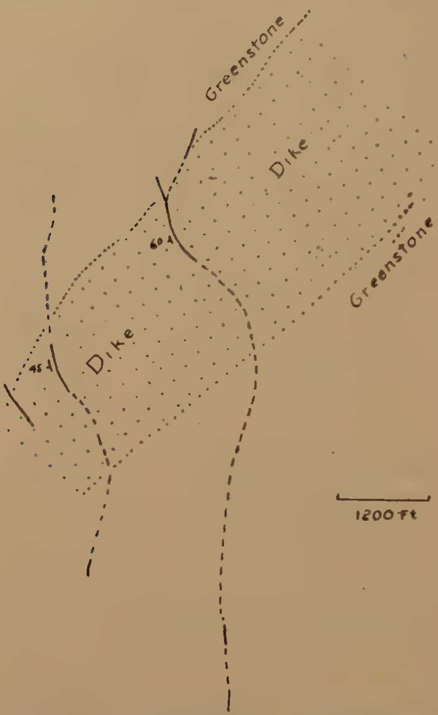

FIG. 19.—DEFLECTION OF VEINS WHERE PASSING THROUGH DIKE. (*After J. M. LeGrange.*)

Productive parts of veins are within dike. Day Dawn, W. A.

RELATION OF OPENINGS TO MOVEMENT

From the foregoing discussion it is apparent that change in the direction of a vein may be occasioned by: (1) movement along a surface that consists alternately of planes of shear and of tension, or (2) movement that takes advantage of pre-existing planes of weakness, or (3) fracture passing through layers or bodies of rock of contrasting strength characteristics.

Width of Opening.—When movement takes place along a zigzag surface, the width of the opening formed bears a simple geometrical relation to the change in direction (here called the angle of deflection) and the amount of movement (assuming, of course, that the rock is strong enough to sustain the open space). For a displacement d along a fracture deflected through an angle θ the width of the opening w is:

$$w = d \sin \theta \text{ (Fig. 21)}$$

As examples, the amount of movement required to produce openings of 0.1 ft. and of 1 ft., respectively, with different angles of deflection are:

Width of Opening, Ft.	Angle 1°	Angle 10°	Angle 20°
0.1	5.75 ft.	0.55 ft.	0.3 ft.
1.0	57.5 ft.	5.5 ft.	2.9 ft.

Thus with a deflection of 10° an opening 1 in. wide is produced by a movement of only 5 inches.

Filling of Openings.—The "openings" referred to in this paper were not necessarily gaping voids for any length of time. Some may have become filled at a very early stage with water or other liquid under hydrostatic pressure, or they may have been filled very promptly with vein matter. There is a good deal of evidence to suggest that in some fissures deposition went on *pari-passu* with separation of the walls.[20] Some authorities have contended that the force of crystal growth has been an active agent in opening fissures, and others make a strong case for hydrostatic pressure of solutions as the force producing the opening.[21,22] While either of these forces, and particularly the latter, may have played a part in separating the walls, it would be expected that if these were the agents solely responsible they would separate the walls of all fissures in any system regardless of the attitudes of the veins. But openings so commonly occupy preferred orientations, which fit into the structural setup, that it is difficult to escape the conclusion that in general the external forces have been at least the deciding factor in separating the walls, even though they may have been aided by forces within the vein.

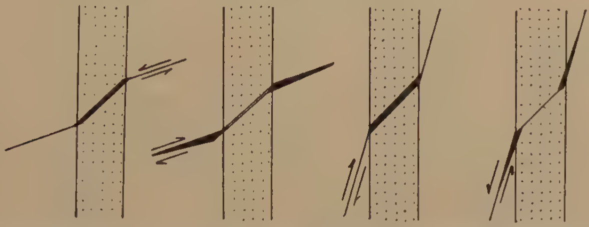

FIG. 20.—FRACTURE CHANGING DIRECTION WHERE CROSSING A BED OR DIKE OF CONTRASTING MATERIAL.

Positions of openings determined by direction of deflection and direction of movement are shown for the four possible conditions. Idealized diagrams.

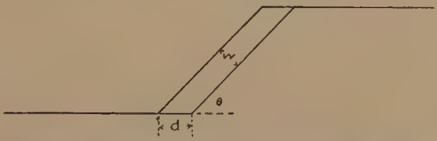

FIG. 21.—OPENING PRODUCED BY DISPLACEMENT ON AN ANGULAR FAULT FISSURE.

d, amount of displacement; *w*, width of opening; *θ*, angle denoting local change in strike of fault. Diagrammatic.

In some cases, particularly at depth, the "openings" probably have an ephemeral existence. It is known, both from experiment and from the observation of underground workings, that under pressures corresponding to depths of a very few thousand feet the walls of large openings tend to fail. Within a relatively short time stopes become filled with slabs from the walls and roof. Thus there is substituted for the actual opening a sheeted zone or a mass of slablike breccia or a region of intersecting minor fractures.* Such conditions are sometimes mistaken for the direct effects of shearing. As will be explained later, they are excellent places for ore deposition.

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* This idea has been developed by Dr. L. C. Graton though never published, so far as I know.

Relation of Pitch of Ore Shoot to Type of Fault.—Geometrical relationships* as well as field observations lead to certain useful generalizations regarding the location of openings on different types of faults.[23,24]

	Dip-slip Faults		Strike-slip Faults	
	Normal	Reverse	Right-hand*	Left-hand
Location of Openings.....	On steeper portions	On flatter portions	On deflections to the right	On deflections to the left

* The horizontal component of movement is designated as right-handed if the farther wall of the fault, as the observer faces it, has been displaced to the right. Conversely for left-hand movement. A moment's contemplation will show that a right-hand fault is still right-hand if the observer faces it from the opposite direction.

On faults having components of movement on both the dip and the strike it is necessary, of course, to take into consideration the actual direction of displacement, not merely the apparent displacement as shown in either a plan or section alone.

Field experience indicates that the *long dimension of an ore shoot on a fault fissure is very commonly at right angles to the direction of slip.* From a theoretical standpoint this is to be expected provided that in the direction of the third dimension the stress orientation and the nature of the rock remain constant. The fact that field observation so frequently corresponds with the theoretical expectation indicates that the ideal conditions are often approximated. Variations from the ideal form are, in some places at least, to be explained by variation in the nature of the wall rock.

Field observation further suggests that epithermal veins, particularly those in Tertiary lavas, commonly occupy normal faults,† whereas veins of the deeper zones commonly occupy reverse or strike faults, or faults that have slipped in directions between the dip and the strike.

These considerations lead to a corollary that ore shoots in epithermal veins are likely to have a flat or gentle pitch. Although there are many exceptions to this rule, the fact that epithermal deposits are common in beds or lava flows having gentle dips constitutes an additional factor in its favor. Ore deposits of the deeper zones may have flat pitches, though vertical or inclined pitches are probably more common.

INFLUENCE OF STRUCTURE ON RICHNESS OF ORE

Every mining man is well aware that the criterion distinguishing ore shoots from the parts of the vein system that are unminable is the total metal content over mining width as expressed in foot-ounces, foot-dollars. or inch-pennyweights. One factor entering into this product is width, and this alone is often sufficient to make the difference between minable and unminable portions. The other factor, metal content per ton, varies in different portions of a vein system, for a variety of reasons, not all of which are well understood. Some are probably not directly related to structure; others probably have a more definite relation to the shape and arrangement of fractures than is generally realized.

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* These considerations, being purely geometrical, are quite independent of any theory of fracturing.

† This generalization is likewise substantiated by Newhouse's compilation.[24]

In my opinion two principles are of prime importance: First, active circulation of ore-depositing solutions provides a constantly renewed supply of mineral matter, whereas stagnant solutions can deposit only the small quantities of metals contained in a limited volume of solution.[25] Thus, contrary to widespread belief, damming, in the sense of impounding, is not a favorable condition; damming, in the sense of diverting and concentrating flow along certain channels, is, on the other hand, conducive to ore deposition. Second, reaction between wall rock and solutions is a potent factor in causing precipitation. Hence large areas of wall-rock surface, as presented by zones of breccia, abundance of inclusions, and systems of ramifying fractures, induce precipitation of metals and also exert the maximum cooling effect on circulating solutions.

Relation of Richness to Width.—In view of these considerations, the portions of a fracture system in which the normal component of stress has been active are likely to be not only wider but also richer,* for the following reasons:

1. The widest portions of veins have offered the channelways for freest circulation of solutions.
2. Open or potentially open portions of a fracture system are places of shattering and brecciation (see p. 83).
3. Portions of a vein system in which shearing alone has been dominant are likely to be clogged with gouge and therefore less permeable.
4. In many veins the ore minerals are deposited later than the gangue. A given thickness of early gangue will nearly or completely fill a narrow vein whereas in a wider vein it will leave openings for the passage of later solutions.
5. Continued or renewed movement[23] on a fracture after some vein matter has been deposited is likely to produce openings in the portions of the vein in which the original opening was greatest, thus permitting introduction of solutions at a late stage.

Ore Shoots Localized by Vein Intersections.—Mining men realize that splits and intersections of veins are favorable places for ore shoots. The view[26] that solutions of different types mingle at such places to cause precipitation is more often quoted in geological treatises than confirmed by underground facts. In rare instances it may be the correct explanation, but in the vast majority of cases the mineralization on both veins near an intersection is identical and does not suggest contrasting solutions, whereas physical facts are quite adequate to account for the concentration of values. Examination of the vein matter at a junction or split usually reveals one of the following conditions:

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* There are, of course, exceptions to this generalization. Sometimes the narrower portions are the richest. The reasons are not always clear, but the following cases occur: (1) some narrow fractures formed late in the process; (2) some broad portions are not parts of continuous channelways; (3) some broad portions were open spaces free of inclusions.

1. The wedge of rock[27] between the two veins is fractured, brecciated or shattered.
2. The vein opposite the wedge is exceptionally wide, as though movement of the wedge had forced the walls apart.
3. One vein has been opened at the junction by movement along the other.

In view of the principles already discussed, the junction under any of these conditions becomes a permeable channelway, and when shattering and brecciation have occurred ore solutions have had access to an exceptionally large surface of wall rock.

Conclusion

In this paper an attempt has been made to describe:

1. The pattern of fractures that might be expected to form under the simplest and most ideal conditions.
2. Some of the complicating factors that result in modification of the ideal pattern.
3. The problems confronting the geologist in analyzing any vein system; i.e., to recognize the departures from the theoretical pattern, to understand their causes and to interpret these causes in terms of rock structure, such inquiry often leading to the recognition of a systematic control in what at first appears to be a purely haphazard distribution of ore shoots.

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DISCUSSION

(E. S. Moore presiding)

E. Wisser,* San Francisco, Calif.—This paper is an outstanding exposition of the method chosen with which to attack the difficult problem of rock deformation. It is in that method, rather than its exposition, that I would find some flaws.

The "mechanical principles" of rock failure by fracture (pp. 66–73) are discussed by McKinstry from the standpoint of the engineering testing laboratory. "When rocks . . . are loaded beyond certain limits, they either fail by fracturing, or yield by 'flow'." This may hold for some tests in the laboratory. In the field, a case of "flow" entirely dissociated from fracture is rare. By fracture I do not mean flow cleavage, slaty cleavage. I mean faults, with distinct, if slight, displacements. The softer the rock, the greater the "flow" and the more of these faults. Beds of soft shale that have clearly "flowed" usually show myriads of minor faults.

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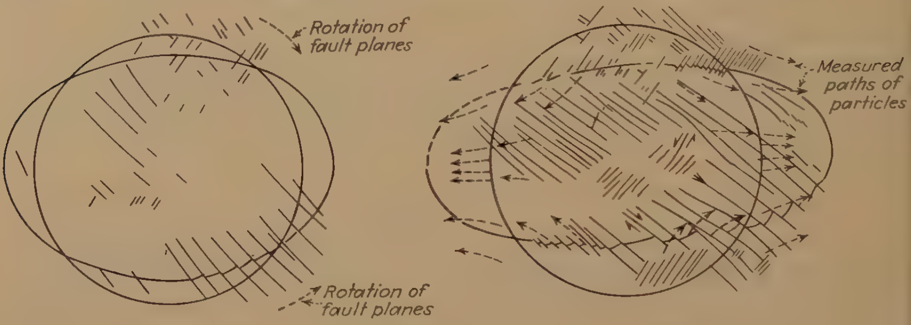
* Consulting Mining Geologist.

These faults are often conjugate shear planes, with a pattern approaching the "ideal" (p. 73). Conjugate shear planes, equally developed, accompany "flow" rather than "fracture." Here some attempts at definition are needed. For any unit of deformation, whether a laboratory test block, a stratum, or a mining district, it is convenient to call a *fissure* any fracture that disrupts the unit by widening of the fissure walls. A *disruptive fault* disrupts the unit by extensive displacement along the fault plane. A disrupted block of ground is no longer a unit; it has lost cohesion, and is broken into two or more smaller units. Fissures and disruptive faults effect deformation by disruption. *Flow*, in contrast, effects deformation without disruption; the deformed unit retains cohesion; it is still a unit, however much distorted. It has "flowed"; nevertheless, it has often also fractured most intensely in the process. This kind of fracturing is different from the disruptive faulting just described but it affords the nearest approximation to the "ideal fracture pattern" of McKinstry found in the field. It is an integral part of flow.



a *b*

FIG. 22.—TOP VIEW OF CLAY CAKE DEFORMED IN EXPERIMENT BY H. CLOOS. Shortening and elongation in plane of paper. Two stages of deformation.

The most striking experimental production of conjugate shear planes is obtained by H. Cloos,[28] who deforms a soft clay cake resting on a wire netting (Fig. 22). The cake may be deformed by tension, compression or shear; the results are the same—i.e., unlike stresses produce like strains. At first the circle inscribed on the clay cake deforms by "flow." No fractures are visible. Soon, however, a finely spaced network of conjugate shear planes appears. Probably they were there at the start, though not seen, since they develop rapidly in number and strength as deformation proceeds. These shear planes "spread" or rotate during the flow, so that the angle between planes of each set widens (Fig. 22). They are antithetic faults;[29] i.e., their displacements are due solely to rotation of their adjacent fault blocks. Fig. 22*b* shows the paths of various particles in the deforming clay, derived from photographs of the experiment at various stages. The paths are hyperbolic, closely resembling those derived by Becker[30] for flow. The particles move in paths always nearly perpendicular to the antithetic fault planes; the moving clay "shoves the fault planes around," makes them rotate. The whole process is one of flow, for the clay cake never loses cohesion; there is no disruption.

Where these shear planes occur, tension fissures never appear. This is easy to understand, once the idea is grasped that the formation of conjugate shear planes is related to flow (Lüder's lines) and not to disruption. With flow, a deforming mass elongates mainly in one direction, contracts in a direction perpendicular to that of elongation. (Like McKinstry, I speak of two-dimensional deformation, with the third dimension remaining constant, for practical purposes.) With fissuring (disruption), a mass may elongate by widening of the fissures; but it cannot correspondingly contract in a direction perpendicular to the elongation, or in any other direction (Fig. 23). There is no flow, only cracking. That is why tension joints parallel to the direction of compressive force and set up by that force never appear with conjugate shear planes in the field (I speak of single-stage deformation). Conjugate shear planes in a deformed mass that has not lost cohesion are expressions of flow. Fissuring is disruption, the opposite of flow.

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[28] References are at the end of the discussion (p. 93).

There is one apparent exception: where one shear set appears to the exclusion of the other, tension-gash or feather-joint branches to such shear planes do appear (Fig. 6) and often are loci for veins. But these single-set shear planes are not antithetic faults; they are disruptive faults unconnected with flow, when accompanied by feather joints. With disruption by fissuring, while the deformed body as a whole loses its cohesion, the individual blocks into which it is disrupted retain theirs. The blocks are competent; they do not flow, but crack. All tension fissures, including these feather joints, are limited to competent rock, rock that will not flow, for flow is the negation of fissuring. (See Fig. 11, the great tension fissures in the Baguio quartz diorite massive.)

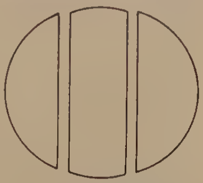

FIG. 23.—ELONGATION BY FISSURING. NO CORRESPONDING SHORTENING.

These statements are contradicted, perhaps, by compression experiments on limestone blocks, with or without high confining pressures. The types of deformation obtained in these experiments do not resemble deformation of major geologic units, for the following reason. The terms "ultimate strength," "brittleness" or "competence"; "ductility" or "incompetence" have no absolute meaning. They are completely relative, and depend, for a given rock, on the scale of the deformation, on the "size of the deformed beam." A test block of limestone in a laboratory is "strong," "brittle," "competent." On the other hand, a massive limestone bed involved as a minor unit in an enormous deformation (e.g., that of the Paleozoic beds in the heart of the Appalachians) is stretched and thinned like a small shale lamination in a minor fold. It follows that to reproduce in the laboratory a miniature but faithful picture of a major deformation, correspondingly weaker material must be used, the greater the scale of deformation investigated. This has been recognized by H. Cloos,[31] M. K. Hubbert[32] and others. To apply ideas on deformation derived from engineering tests of limestone blocks directly to large fractured units of the earth's crust is unsound.

Common field observation shows that most fissure veins are confined to competent rock; competent, that is, in relation to the scale of deformation. Granitic massives are competent in relation to any but an Alpine scale of deformation; competent rock like granite tends to fissure, to crack, instead of to shear, to flow. It will shear, however, where the scale of deformation is large enough (Butte); and it will crack where it forms a relatively long and narrow mass between soft, incompetent material (Hog Mountain, Alabama[33]). Ordinarily granite is too competent to shear, too massive to crack; this explains why the prospector thinks it unfavorable. With the scale of deformation common to most mining districts, a wide range of rocks is competent enough to crack, but at Ouray wide veins in brittle Dakota sandstone peter out abruptly in the overlying Mancos shale.[34] Here a force acting vertically from below cracked the sandstone and forced the shale to flow.

If these ideas are correct, equally developed conjugate shear planes, connected with flow, are unfavorable signs for ore. This explains why they are so rarely seen in mining districts. Disruptive shear planes, on the contrary, unconnected with flow, are common in mining districts. Productive veins favor competent rocks, and competent rock does not flow. The disruptive shear planes form one set only, the commonest case in mining districts. Where the second shear set appears, these usually are antithetic faults, and they indicate soft rock, flow. Material may flow by shear as easily as by simple compression; where it does, instead of the formation of two equally developed sets of conjugate antithetic faults (Fig. 22) there develop one or more disruptive faults, whose planes, unlike those of the antithetic faults, do not rotate. The greater the shear, the greater the displacement on these disruptive faults. There develop also, in material that flows by shear, a set of antithetic faults of which the planes do rotate (Fig. 24). As stated on page 67, where a disruptive shear plane faults competent rock, there is little or no flow. There is cracking, parallel to the compressional component of the shearing stress (Fig. 24). Tension gashes or feather joints result; these form most of the veins in regions deformed by shear.

Equally developed sets of conjugate shear planes, characteristic of flow by simple compression, are rare not only in mining districts—they are rare everywhere; because most deformed regions are heterogeneous in structural makeup. In particular, mining districts are often associated with plutonic massives intrusive into softer stuff. A simple compressive shove acting on such a region is transformed into one or more shearing couples, because the massive tends to resist the force and stand fast, while the softer material tends to flow past the edges of the massive. The productive veins of such a district form in or near the massive, while the softer surrounding material is full of barren, gougy faults. The edges of the massive, if at all straight, form loci for disruptive shear faults; they act as cutting tools. Most shear patterns seen in the field are asymmetric: one shear set shows far more displacement than the other; and always the stronger set was localized by a preexisting feature like the straight edge of a granitic buttress.

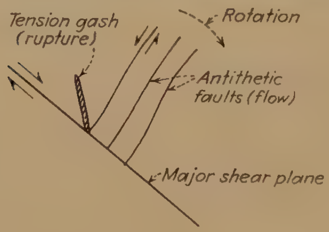

FIG. 24.

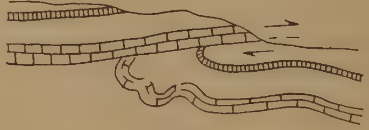

FIG. 25.

FIG. 24.—MAJOR OR DISRUPTIVE FAULT, WITH ANTITHETIC FAULTS WHERE SHEARED ZONE FLOWS, AND TENSION GASHES WHERE IT CRACKS.

FIG. 25.—FLAT THRUST.

Take the case of horizontal compressive force. The resulting deformation if by faulting takes place in one of two ways. Where the force is exerted on flat-lying beds of competent and incompetent material, flat "overthrusts" are produced. Generally, a competent layer is thrust over an incompetent layer, and the latter is pulled into drag folds (Fig. 25). Here the preexisting structure used by the force is a bed plane. The other kind of faulting results where soft but unbedded material, or bedded material in large-scale examples, is intruded by a steep-sided granitic massive. Edges of the massive that are approximately straight and not oriented perpendicular to the direction of shove localize steep planes of disruptive, horizontal fault movements. In the first case, the lateral shove induces a shearing couple acting in a vertical plane; in the second, a shearing couple (or several) is induced that acts in a horizontal plane. In neither case is there likely to be an "ideal fracture pattern" of shear planes. Where either type of deformation acts on soft rock, the antithetic set of shear planes may form; where either type acts on brittle rock, tension gashes form instead. The ideal fracture pattern of McKinstry is never found as a unit at a given place.

The second case, that of shear acting in a horizontal plane, is illustrated at Lordsburg, New Mexico,[35] where a mass of granodiorite with a fairly straight, steep northern edge intruded unbedded, soft basalt (Fig. 26). Compressive force acting as shown used the steep northern edge (and others) as a cutting tool, forming the Anita-Atwood shear fault zone. Lasky shows that most of the fault movements in the district were subhorizontal. The Anita-Atwood disruptive fault zone lies mainly in the soft basalt, along the edge of the competent granodiorite. Hence a complex fault pattern resulted, remarkably similar to McKinstry's Fig. 12 showing stress orientation between two moving shears. Little ore was localized in the Anita-Atwood fault zone; what little there was (Anita vein) lies directly against, or within, the competent granodiorite. This is because the soft basalt, however much it was fractured and faulted, nevertheless flowed, and the flowage is plainly seen in the drag and distortion of the link fractures between the two main shear planes. Had fracture occurred along McKinstry's planes of maximum shearing stress (Fig. 12), they would show precisely similar distortion.

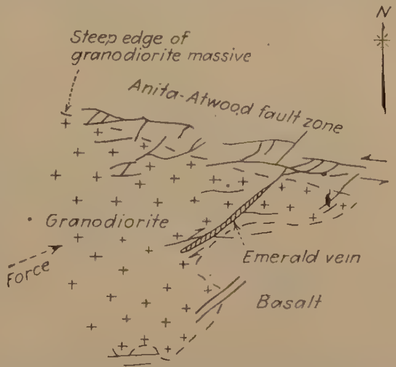

FIG. 26.—DIAGRAMMATIC SKETCH MAP OF LORDSBURG MINING DISTRICT NEW MEXICO. (AFTER S. G. LASKY.)

The competent granodiorite mass was too massive to crack except at the north horn of the crescent formed by its eastern edge. There it cracked to form the Emerald vein, the main producer. This is a great tension gash. Lasky shows well how the Emerald ore body is limited to the granodiorite, which cracked, and avoids the basalt, which flowed. The Lordsburg fracture pattern fits only the part of the ideal shear diagram that contains one shear set and feather joints; the other, antithetic set is lacking in the competent granodiorite, though probably it is present in the soft basalt.

The Emerald vein, according to the evidence, formed by opening of the walls, by fissuring. Continued fissuring extended the fissure along its strike; the fissure cut clean across the north horn of the granodiorite crescent. Fissuring then had to stop; the fissure became the locus of disruption by shear; the northwest wall moved northeast with respect to the southeast wall. There resulted late and post-mineral strike faulting with development of gouge. This is the reverse of McKinstry's postulation (p. 76) that continued unchanging stress causes the walls of shears to separate. Surely the Lordsburg case is the more common in the field: strong post-mineral faulting along a vein fissure. Compare the Coeur d'Alene district and many others. Gouge feeds on gouge. With continued application of the same force, once a shear, always a shear. Competent rock, especially a tabular mass surrounded by incompetent rock, will fissure as long as the fissure is confined to the competent rock mass. Once such a fissure grows clean across the competent block and cuts it in two, continuation of the shove that caused the fissuring will produce shearing movements on the former fissure, as with the Emerald vein at Lordsburg.

The Real del Monte district (Fig. 27) resembles Lordsburg, without any visible granitic buttress. Here the preexisting planes that induced disruptive shear faults were old normal faults. The normal faulting gave them gouge; lubricated them. A moderate compressive force from the east is thought to have operated after the normal faulting. The ground, already disrupted into blocks with fairly steep sides, was shoved westward and the movement was accompanied by differential movement of these blocks, giving subhorizontal shearing displacements on these old normal faults. Here again there is no ideal fracture pattern, no pattern set up initially by compressive or shearing stress. The major shear set was localized by preexisting structures. Here no feather joints formed because the andesite country rock was not competent enough in relation to the large scale of the deformation. The north-south vein fractures seem to me to belong to the antithetic fault set and to represent a form of flow,[29] in spite of the fact that they are mineralized. They may have a different origin. Whatever their origin, they carry the ore, while the major disruptive shear planes, with heavy gouge, carry little. The veins have little or no gouge, and show some characteristics of tension fractures. In a rough sense, then, they are comparable to the Emerald vein at Lordsburg except that they never became the loci of strong shear faulting, as did the Emerald vein after mineralization.

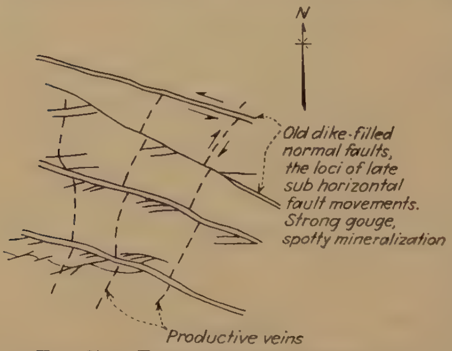
N
Old dike-filled normal faults, the loci of late sub horizontal fault movements. Strong gouge, spotty mineralization
Productive veins

FIG. 27.—DIAGRAMMATIC SKETCH MAP OF PART OF REAL DEL MONTE MINING DISTRICT, MEXICO.

It would seem, then, that the influence of preexisting structural features in the formation of fracture patterns attributable to shear is underestimated in McKinstry's paper (pp. 76–78). They are not merely a factor; they dominate. Further, ore bodies not along major planes of disruptive shear are usually in fissures due to cracking and not directly connected with shear. Ore bodies along the planes of disruptive shear do show the zigzag control so well described by McKinstry (pp. 82–83) and by Newhouse.[36] But I have shown how these major shear planes, with relative displacements of their walls, may originate through some such preexisting structural feature as the straight edge of a plutonic massive. Such features are unrelated genetically to any stresses causing relative movements of the fracture walls. They twist and turn erratically, and in a general way the shear plane is apt to turn with them. No amount of theorizing can predict such turns. By knowing the direction, and perhaps the amount, of the relative movement of the fracture walls, we can tell what attitudes of the fracture make for open spaces and ore; but we cannot predict where such attitudes may be found by having recourse to the supposed stresses that caused the fault movement.

Zigzag control often is seen in the field; but with epithermal precious-metal veins at least, it is usually local, and it fails signally to explain the major ore bodies, which, as McKinstry says, are apt to be long horizontally and short vertically. The Tomboy ore body at Telluride was almost continuous for 2000 ft.; that of the Camp Bird, for 1200 ft. Each long shoot *was identical with the lode itself*, disappearing only where the lode pinched and quit.[37] What little evidence there is for faulting along the Camp Bird fissure indicates horizontal movement, not dip-slip as required by McKinstry (p. 84).

There is an ore shoot in Mexico over 3000 ft. long, nearly 2000 ft. high. A plan of the vein shows swings to the right and swings to the left, by the dozen; sections show sharp local flattenings and sharp local steepenings; ore persists throughout.

I have said that most productive veins are found in competent rock, and that most open fractures in competent rock are due to cracking, the result of the compressive component of shear alone or, *more commonly, to simple compression without* shear. The simplest, and probably the commonest, way in which competent rock cracks is by uplift, as a result of a vertical force acting from below on a brittle layer between softer layers (Ouray). With such fissuring, the walls pull apart, admitting the vein matter. Minor changes in attitude of the vein fracture are unimportant;

this is usual in the field. To form a fissure, competent rock is needed, and an ability of the cracked rock to glide away from the plane of the fissure in each direction. This ability is supplied, for a brittle layer between softer ones, by the soft material, which flows, allowing the brittle layer to crack. Most cases of "trapping" are of this kind: ore in a cracked brittle rock quits abruptly in the soft stuff above.

I think McKinstry has underestimated the frequency with which vein fractures form or reopen, as vein matter deposits. It seems to me that this is nearly universal. No fracture opens equally everywhere. Fractures opening in places at the time of ingress of ore solutions receive ore shoots at those places; elsewhere they are barren.

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H. E. McKinstry (author's reply).—It is a decided satisfaction to note that a man whose field experience is as inclusive as Mr. Wisser's finds himself so well in agreement with the ideas that I have expressed. For although a casual reading of his discussion might suggest that his views are strongly in conflict with mine, I am convinced that a thoughtful perusal of both contributions will reveal little between them that is irreconcilable.

First, the term "flow" has been used in various senses. Many geologists familiar with strongly metamorphosed terrains would hold that the type of flow that is accomplished by recrystallization produces rocks that show little evidence of faulting or, at any rate, of conjugate shears. Other types of flow, exemplified by the deformation of clay, are accompanied, as Wisser shows, by the development of such shears. I would question, however, whether the distinction between these surfaces of slip and disruptive faults is, in principle, more than a matter of scale and degree. In any case, antithetic faults, as well as disruptive faults and tension cracks when they occur, occupy the positions that would be called for by an analysis of the stresses unless complicating factors intervene.

One need not resort to incompetent failure, however, in order to find conjugate shears. The vein pattern of the Siscoe mine and of the Wood's Point dike bear every resemblance to complementary sets of disruptive fissures, and the Grass Valley district, if one may accept the interpretation early suggested by Lindgren, offers a still more famous example. In these cases, one must, to be sure, view the district as a whole to see the complete pattern. In any one place a single shear-direction with or without fractures in the tension direction is all that can be observed. But these examples, I quite agree, are the exception rather than the rule. Wisser has shown how failure on one set of fractures relieves certain stresses and tends to obviate the necessity of failure on certain other planes. Thus, as I have said (p. 73) any one or even two of the three directions of fracture may fail to develop. (I am almost willing to say *must* fail to develop.) And it is quite in accord with this view that many veins represent failure along tension cracks to the partial or complete exclusion of failure by shear. Wisser's statement that "the ideal fracture pattern is never developed as a unit in any one place" is only slightly more emphatic than my observation that "such a pattern . . . is rarely if ever found in natural examples."

Perhaps misunderstanding arises from my use of the phrase "ideal fracture pattern." Admittedly this is a makeshift term; I tried hard to think of a better one. "Hypothetical" or "theoretical" rather than ideal, perhaps? The pattern might be compared to the triangle used on a drawing board. The draftsman may, for reasons of his own, fail to draw lines parallel to all three sides of it, but any line that he draws is parallel to the direction prescribed by the triangle or pattern; parallel, that is, if the paper is smooth. If there are grooves in the paper the pen may wander and when it does we are very much concerned with the cause and direction of the grooves.

Thus, if there is one point that I wished to bring out more than any other it is "the influence of preexisting structural features in the formation of fracture patterns," and if, as Wisser believes, I have underestimated this influence I am glad that he has amplified the discussion of this subject. Openings along preexisting structures cannot, however, be divorced from the stresses that caused the opening even when their position is predetermined, and I am still unwilling to admit as a general proposition that "we cannot predict where favorable attitudes can be found by having recourse to the supposed stresses that produced the movement." I submit that the movement, whatever its amount and direction, is a result of force resolved along surfaces of weakness whenever such are available and that this causal relationship need not always be discarded as useless even though at times the results may be too complex to decipher. Where the surfaces of weakness consist of bedding planes or of parallel dike margins, for example, their attitudes usually may be predicted in advance of development. Which attitudes are likely to be favorable may be best determined often by local experience but if this is insufficient "theorizing" often provides a solution that is well worth testing.

Under appropriate circumstances competent rocks yield to fracture so much more effectively than incompetent formations that this influence alone may be sufficient to localize ore shoots. I am glad that Wisser has remedied my seeming neglect of this important principle. Yet competency in itself is not under all circumstances a favorable factor. One need only recall that in certain portions of the Porcupine district highly incompetent slates between competent lava flows have been the loci of exceptionally rich veins and that in Bendigo the saddle reefs are not, as a rule, in the most competent beds.

That zigzag control is by no means the answer to all problems in ore localization, I readily agree, but I believe that it is commoner than is generally realized. Often it is not apparent until the structure is carefully contoured by methods of the sort described by Conolly. Where a vein is so strongly mineralized that even the "unfavorable" portions are productive, there has usually been little incentive to study the minor variations in attitude and compare them with the distribution of values. No such study, so far as I know, has been made of the Camp Bird vein, and had it been made it might have served no practical purpose. But in a near-by vein, the Handicap, where the mineralization is in many respects similar (though much less rich) there is a conspicuous relation between the distribution of values and the changes in strike, a fact quite in accord with Wisser's observation that the displacements in this locality have a strong horizontal component. I hope that I did not give the impression that vertical movement is the only means by which differences in competency can be translated into favorable structures.

Nevertheless, in certain epithermal precious-metal veins, including those of the far from negligible districts of El Oro and the Comstock Lode, the ore shoots appear to have been localized most generously in places where normal faults or their branches approach vertical attitudes, thus swinging toward the "tension" direction.

Wisser's criticism that my approach is theoretical may or may not call for defense. One might indeed infer from the arrangement of my paper that I had first concocted a theory and then sought examples to bolster it up. Actually the sequence of the inquiry was just the reverse. Field observations through many years kept raising question after question until I was gradually driven to experiment and mathematical analysis for some usable rationalization of seemingly unrelated facts. When experimental results offer analogies to field observations, one is fully justified in accepting any enlightenment that they may present and until our colleagues the geophysicists are in a position to tell us in numerical terms the magnitude of tectonic forces, and the strength characteristics of rocks under geological conditions, it is difficult to say whether laboratory tests on limestone blocks or on lumps of clay afford the more "unsound" analogies to natural deformation. Some rocks appear to have behaved like the one, some like the other and some like neither.

It is only natural that two geologists whose field experience has been in different regions will receive divergent impressions of the relative importance of various processes and the applicability of various methods. In spite of differences in viewpoint, some of which I have discussed, I feel that many of the points that Wisser brings out are to be regarded rather as instructive illustrations and amplifications of the principles that I have attempted to assemble than as proof of their inapplicability. His discussion, and particularly that relating to the contrast in mode of failure between competent and incompetent rocks, is a contribution that merits very careful attention.

The Environment of Ore Bodies

By Edward Wisser,* Member A.I.M.E.

(New York Meeting, February, 1938)

The environment of an ore body is taken to mean not only its physical surroundings but every factor, passive or active, that conditioned the ore shoot, saving only the original composition of the solutions that formed the shoot. Collection of data related to the shape and characteristics of veins should be followed by correlation of the data and the formulation of generalizations regarding ore formation. The nature of the criteria used in arriving at these generalizations is discussed. Certain of the criteria, when used with an understanding of their underlying causes, become "ore-guides." In the course of his study the geologist must not confine himself to the immediate surroundings of the veins, but should attempt to work out the geologic history of events culminating in the crucial epoch for any mining district, the period of mineralization. The work may involve study of features far removed from the veins and related to them only indirectly. It commonly means thorough study of the geology of the entire region surrounding the ore deposits.

The following question has been suggested for discussion:† "Are there any criteria by which one can determine when mining operations have reached the roots of an ore deposit?"

The question deals less with the roots of a particular ore body than with the lower limit of the vertical range within which ore bodies may be expected. It concerns a critical line upon the longitudinal vertical projection of a vein.‡ Below this line it is useless to look for ore shoots; above the line exploration below the bottoms of individual ore shoots may be justified. Can we learn to determine the position of such a line?

In some multivein districts the line for any given vein may be approximated by simple interpolation or extrapolation. Where this is possible the bottoms of the lowest ore shoots in the various veins are points on an imaginary, gently rolling surface. The trace of this surface upon the vein is our critical line for that vein. The imaginary surface rolls so gently that it may be projected from two or more known veins to an unexplored vein near by. Here is a criterion for the bottoming of ore that has nothing to do with changes in the appearance of the vein in question; it rests solely on the depth at which the ore bottomed in adjacent veins. The method is not applicable in districts only slightly explored in depth, nor where the lower limit of the ore-bearing horizons

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‡ The present discussion is confined to veins.

on the various veins varies so greatly that no logical "imaginary surface" can be set up.

If interpolation cannot be used, the question may be answered by certain changes in the appearance of the vein itself, which appear where exploration has reached the lower limit of ore body expectancy. They are usually mineralogical or textural. For example, such a diagnostic change might be a sudden increase in the proportion of a vein mineral not ore, such as calcite; if the veins of a district turn to barren calcite below the ore horizons, a bottom level carrying ore but showing increasing calcite would suggest the bottoming of ore. Or the change might be one from "live-looking" quartz characteristically associated with ore to dead silicification quartz, a feature frequently found in veins below their productive horizons. The operator notes that such changes take place in each vein just where the lowest ore shoots bottom. He uses these changes as criteria for the bottoming of ore anywhere in the district, until, as sometimes happens, he finds a heretical vein that defies his rule, and carries ore beneath the horizon at which his supposedly unfavorable changes appear. He then resignedly admits that "ore is where you find it."

This paper deals with the nature of criteria related to ore occurrence. The question, "Are there any criteria by which one can determine when mining operations have reached the roots of an ore deposit?" concerns the exploration of known ore downward. It aquires a broader interest if this implied situation is reversed. Consider a vein exposed at the bottom of the vertical range of ore body expectancy and as yet unexplored elsewhere. Features indicative of the roots of ore shoots point upward toward ore. If the miner recognizes such features where he has exposed the vein he will raise into ore; otherwise he may sink and will find no ore. Thought of in this light, the question may be expanded: "Are there any criteria by which one can determine whether a vein exposed, thus far, in waste only, is likely to yield ore somewhere, and are there criteria to show, in addition, whether a given exposure in waste lies above, to one side of, or below the place where ore might be expected?"

The mining geologist is inclined to overemphasize the evaluation of ore; he is overly concerned sometimes with the question: How did this ore form and why? His principal function, in practice, is to evaluate waste. As Lindgren[1] says: "When the miner has an abundance of ore he gets along comfortably without the geologist, but when ore resources grow slim, the geologist is called forthwith." When ore is giving out, most exposures are in waste.

It is true that the most successful method of finding ore today is to seek duplicates of settings known to have produced ore. Since such settings may involve changes in the strike of the fracture explored, cross-faults, fracture intersections, etc., exploring them may have little to do with the evaluation of waste in terms of ore. Given, perhaps, a fracture about which nothing is known except that it is pre-mineral, and a supposedly favorable but unexplored setting, we head straight for the heart of the setting and often find an ore body. Ore shoots, however, are commonly small targets to hit, and structural or other control of ore shoots is seldom discerned precisely enough so that an exploratory working, say a crosscut, can be so directed as inevitably to cut the heart of an ore shoot. The usual case, even though the exploration is in the end successful, is to cut a "promising" but low-grade vein where we had hoped to cut ore. Most ore shoots lie encased in a much larger body of low-grade vein material. Since the reasons for localization of these large gangue bodies are frequently manifest, it is often not difficult to find these bodies. The problem is to evaluate them. If we can learn how to tell whether a low-grade body of vein matter is likely to carry an ore shoot, and if so, where the shoot probably lies with respect to the exposure, we should be able to find ore much more quickly and much more cheaply than we do at present.

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[1] References are at the end of the paper.

To accomplish this purpose we must study carefully and systematically the environment of ore bodies. We must learn how veins look in ore, at the edges of ore, above and to one side of ore; in short, we must study vein morphology. Through this study we should accumulate data not merely of immediate, "practical" use to the operator, but bearing on broad generalizations as well. There is a present need for reclassification of veins without regard to current theories of genesis, on the sole basis of common features of morphology. While our present classification of hypogene epigenetic deposits into epithermal, mesothermal, etc., rests largely on this method, all generalizations need periodic testing. Lindgren, a pioneer builder of the accepted classification of ore deposits, says:[1]

> Comparative studies are needed of certain classes of veins—for instance, gold-quartz veins—the common features, the relation of depth to structure, the relation of composition of the ores to structure and depth . . . What are the common features of epithermal veins?

Sales, in his discussion of Lindgren's paper, voices a reasonable objection to the study and correlation of vein morphology:

> The economic geologist . . . rarely finds two mining districts with identical geological conditions. Each district has its own problem. Successful search in one district may or may not result in discoveries applicable to others.

Here is the nub of the problem; this conviction discouraged our operator, whose criteria for the roots of his ore shoots failed him. Is not this failure inherent in the use of empirical criteria without some understanding of their underlying causes?

Empiricism and Analysis

The Pitfall in Empiricism.—The use of empirical "ore-guides" has found much ore; but as Sales implies, overextension of the method often leads to costly failure. Empiricism embodies an assumption perhaps not evident at first glance. It is this: that like effects spring from like causes, and therefore necessarily have a common meaning. Unfortunately, similar effects are sometimes produced by radically different causes. Where conditions of vein formation differ in two veins, a feature diagnostic with respect to ore in one vein may be present in the other vein, but may mean something utterly different. There follows an example from a district of epithermal precious-metal veins in andesite studied by the writer.

In testing hydrothermal alteration of the wall rock as a possible guide to ore, the following facts were learned: With some veins strong alteration haloes enclosed ore shoots, while the stretches associated with weak alteration were barren. But other productive veins showed as a rule weak wall rock alteration, and occasional haloes of strong alteration showed no spatial relation to ore shoots. Weak alteration, therefore, would discourage exploration on certain veins; but if it were allowed to prevent exploration on others, important ore shoots might be missed. The suggestion is, of course, that conditions of alteration and vein formation were different for the two types of veins. Not knowing these conditions, it would be necessary to find at least one ore body enclosed in strong alteration before we could say that strong alteration is a guide for ore on that vein; and to find another, on another vein, associated with weak alteration, before we could say that for that vein strong alteration is not necessary for ore. Every vein is thus a law unto itself.

Use of Multiple Criteria.—What we need is a second criterion by which to recognize these two vein types *before a single ore shoot is found.* Such a criterion would not guarantee ore, but would tell us whether, if ore is found on a given vein, it will or will not be enclosed in a strong alteration halo. Study of the vein morphology of the district supplied this criterion. Detailed mapping of explored veins showed that those striking east-west had their ore shoots commonly encased in strong alteration haloes, while those striking north-south showed as a rule weak alteration and no spatial relation of the stronger alteration to ore shoots. So far the study has been purely empirical; the pitfall of empiricism remains so long as we lack understanding of the reasons for the different behavior of the east-west veins, on the one hand, and the north-south veins on the other. Nevertheless, the empirical use of multiple criteria does reduce the chance of costly failure in exploration.

Empirical Criteria and the Key Concept.—Correlation of vein-morphology studies in the district brought out a third criterion. One of the rock formations is an andesitic breccia with a soft, tuffaceous matrix. The following relations of this breccia to ore shoots in the veins traversing it were discovered: The ore shoots on certain veins completely avoided the breccia in favor of a harder formation immediately beneath it. The ore shoots in other veins formed indiscriminately in the breccia and in the formations above and below it. The breccia, therefore, *per se,* is a treacherous guide for or against ore. But the ore shoots that avoid the breccia occur in the east-west veins, and are encased in strong alteration haloes; while those that disregard the country rock lie almost exclusively in the north-south veins, where alteration is commonly weak and seldom spatially related to ore shoots. Based on pure morphology, the veins described may now be grouped into two classes:

1. East-west veins; ore shoots encased in strong alteration haloes, barren stretches show weak alteration; ore shoots avoid the soft breccia.
2. North-south veins; alteration usually weak, and showing little relation to ore shoots; ore shoots disregard the nature of the wall rock.

District morphological study brought out still another significant fact: the veins of class 1 are usually massive, sometimes symmetrically banded, and suggest deposition in preëxisting open fissures; those of class two commonly show intermineral fault movements, many generations of vein fillings, and other characteristics suggestive of fracturing during vein formation. Up to this point, facts of observation have been correlated; but here an inference is made. The inference regarding mode of vein formation suggests a theorem: Suppose the east-west veins were inert during the period of mineralization, and that the north-south vein fractures were forming and being subjected to fault movements at this time. Will this notion explain all the differing characteristics of the two vein types? Let us analyze the data and test the theorem.

If the east-west veins, class 1, formed in fractures antedating the mineralization, and if the fractures were neither opened nor closed nor affected by stress in any other way during the period of mineralization, both the solutions that altered the wall rock and those that formed the veins must have utilized whatever openings along these fractures had been prepared for them. Inert fractures tend to preserve their open or permeable spaces in competent rock only; openings originally formed in soft rock squeeze shut with time. The altering and the vein-forming solutions would be apt to use the same channels; and since the fractures were there throughout the period of alteration and mineralization, time should have been available for intense and widespread alteration of the walls. Tight portions of the veins might well have been nearly as impermeable toward the altering solutions as to the vein-forming solutions. The ore shoots would then be encased in strong alteration haloes, since the solutions responsible for the alteration and those that formed the shoots utilized the same channels. The barren vein segments would be associated with weak alteration, for channels were lacking both for the altering and for the vein-forming solutions. If these fractures had squeezed shut in the soft breccia before the time of vein formation, ore shoots would avoid the breccia because they would lack spaces there in which to deposit.

On the other hand, if the vein fractures of class 2 were forming at the precise time of vein formation, and if, as the veins suggest, each opening as it formed was instantly sealed with vein matter, the altering solutions, which antedate the bulk of the vein matter, would have scant access to the openings at all, and insufficient time to effect important alteration of the walls. Further, study of these veins suggests that the vein fractures did not open over their entire lengths at one time; the slight intermineral movements that kept reopening them occurred now here, now there, along the fractures. The results were, first, weak alteration as a rule; second, a lack of spatial relations between the stronger alteration haloes and ore shoots. For, unlike the channels along the fractures of class 1, the channels of the fractures of class 2 were continually shifting, as the loci of intermineral fault movements that made channels shifted from place to place along the fractures, and the vein-forming solutions would seldom utilize the channels used by the altering agencies. The third result might logically have been disregard of the rock formations by the ore shoots, for the following reasons: The veins grew by accretion, by the successive creation and immediate filling of openings, usually small. There was no need for large openings to exist at any stage. Fracturing in the soft breccia tended to dissipate itself along many close-spaced parallel planes; the vein matter was thereby furnished multiple loci of deposition, and the weakness of the rock encouraged the formation of more and more of these minor fractures as the intermineral shattering proceeded. In the harder rock the fracturing was simpler, more concentrated into master breaks; here the intermineral shattering tended to break the quartz already deposited, instead of the wall rock, but otherwise the mode of vein formation was essentially the same. The veins are about equally strong in soft and hard rock.

The theorem appears to hold up; it is a plausible key concept to explain the facts of observation. Why were the east-west fractures, class 1, inert during the period of mineralization and those of class 2, the north-south fractures, active tectonically? Our inference has been exploited to the limit; it has explained some facts, but has also brought up another question. To answer this question we turn again to facts of observation; but we know in advance that finding the facts will lead to the making of another inference. Thus the geologic study of a district, and any piece of original scientific research, is a constantly alternating succession of fact-finding and inference. The facts suggest the inference; new facts test it, and suggest constantly broader generalizations that should lead, if we have not fallen into pitfalls on the way, to a plausible theory that will explain those things we are seeking to explain. We cannot prove anything in geology: we can only produce a greater or smaller volume of evidence converging to support a theory that seems to explain the facts.

I shall go no further with the discussion of the veins of classes 1 and 2, except to say that the key concept of inert and active vein fractures was tested by independent evidence, divorced from the mineralization. Some of this evidence involved the relative ages of certain dikes and other intrusive bodies; some involved tectonic experiments. Inferences resulting from these new facts suggested a comprehensive theory of vein formation for the district that seems to explain the facts. In the light of this theory, facts of observation have been discriminatingly used as criteria in the search for ore, and ore has been found. The interrelation of fact and inference, of empirical criteria and analysis, cannot be too strongly emphasized.

Environment of Ore Bodies

It must be plain that in gathering the evidence to form a workable theory of vein formation, we cannot, necessarily, stop at the veins themselves. In the case discussed, the whole district was combed over for evidence bearing on the relative ages of the fractures and veins, and on the nature of the stresses active before, during and after the mineralization. Earlier in this paper the word environment was used in the sense of the immediate surroundings of ore. Evidently in a broader sense it may include the whole district. But the word environment may be used in a sense still broader. In the life sciences, the environment of an organism involves every factor, saving heredity, that affects the form and actions of the organism. There is here a parallel. The analogue to the heredity of an organism is found with ore deposits in the original composition of the solutions that formed them. That composition is usually independent of conditions at the seat of ore deposition. The heredity of an organism may be equally independent of its environment. The environment of an ore deposit comprises not alone its surroundings but all the circumstances, static and dynamic, saving only the composition of the solutions that formed it, that influenced the way in which the ore was formed, and the present appearance of the ore body.

With living organisms, dynamic as well as static factors of environment may be studied more or less directly. With ore deposits, static factors, such as wall rocks, fissures antedating the mineralization—in a word, the passive framework that received the ore—may be studied, perhaps, with little recourse to inference. But dynamic factors of environment, such as variations in the pressure, temperature and concentration of the solutions, and stresses operating during the mineralization, must all be inferred from the traces they may have left behind them. It follows that a study of the factors that make ore or waste, the study of the environment of ore deposits, may never be dissociated from inference.

Method of Portraying Vein Morphology

A great help in the correlation of facts of observation is their convenient presentation. Geologists have failed to utilize to the full the possibilities of a valuable contrivance, the longitudinal vertical or plan projection of a vein. Schmitt[2] uses projections in his method of indicating probable extensions of ore shoots by equal-ore-width or equal-ore-value "contours." Conolly,[3] in an equally valuable paper, shows irregularities in the vein surface, equal-ore-value contours and equal-quartz-width contours upon plan and vertical projections.

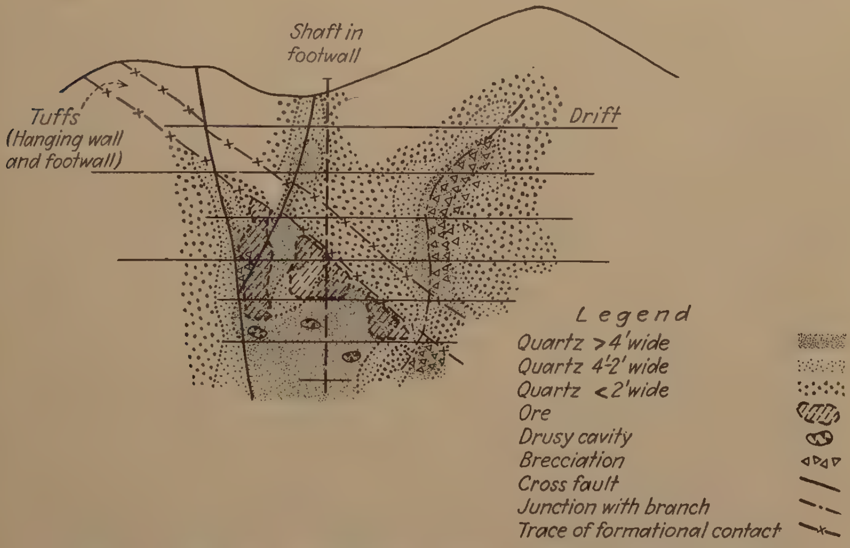

FIG. 1.—GEOLOGICAL VERTICAL PROJECTION OF A HYPOTHETICAL VEIN.

Many other features can be shown on such projections. For example, the distribution of ore minerals and that of other metallic minerals such as vein pyrite; the distribution of gangue minerals such as quartz and calcite, and the textural varieties of the same mineral (coarse equigranular quartz, chalcedonic quartz, etc.); variations in the intensity and nature of the alteration halo in the vein walls. Also, the traces upon the vein of cross faults, dikes and veins; lines of junction of vein branches; traces on the vein of rock-formation contacts in the walls; structural peculiarities of the vein, such as zones of brecciation, areas of drusy cavities or of crustiform banding, etc. A few such features are shown on the accompanying vertical projection (Fig. 1). It is rarely convenient to show them all on one projection. They may be grouped into mineralogical, structural features, etc., and shown on tracings to permit superposition. The projections must be used, of course, in conjunction with geologic level maps and vertical cross sections.

These geologic projections bring out conveniently the relations of ore to gangue, and of both to the other features shown. Relations that appear significant become criteria for the exploration of other veins. Such use, however, must be accompanied by critical analysis, as I have shown. A few examples will further illustrate the point.

Use of the Geologic Projection

1. *Ore-solution Channels.*—The channels used by the vein-forming solutions may be suggested by a projection. A discovered channel may guide us to an ore shoot if we follow it in the right direction. A well marked band of wide quartz leading upward from the lower limit of exposures, and spreading out above suggests that the vein matter of the upper levels ascended along a channel once open but now marked by the quartz band. If the spread-out quartz carried ore and the band was barren, the finding of a similar band elsewhere and unexplored in the upper levels would lead to exploring these levels, preferably by following the band upward.

But the notion that the quartz band below the ore marks the channel up which the ore ascended is solely an inference. To test it we appeal to independent field facts and their corresponding inferences. For example, the geologic projection may show high-temperature minerals in the quartz band, but not in the spread-out body of quartz above it that carries ore shoots. According to present theories of mineral zoning, high-temperature minerals commonly lie between low-temperature minerals and the source from which both types were derived. Hence the distribution of the high-temperature minerals in this case would bolster the notion that the quartz band marks a trunk channel for the vein matter. But the zonal theory is an inference based on facts of observation in many camps.

2. *Spatial Relations of Gangue Bodies and Ore Shoots.*—These are readily shown on a geologic projection (Fig. 1). An ore shoot usually lies within a larger body of low-grade vein matter; it is sometimes coextensive with such a body; occasionally it lies by itself, entirely separated from the bulk of its gangue minerals. The causes for localization of strong gangue bodies are often apparent on a geologic projection. The common gangue minerals, such as quartz and calcite, usually formed in great bulk, and needed open or permeable places in which to deposit. Where gangue and ore came in together, what explains the localization of the gangue must largely explain that of the ore, for the gangue bore the ore minerals with it.

If, on the other hand, the ore minerals deposited later than the bulk of the gangue, ore control may differ from gangue control. Manifest causes for gangue control may have no meaning in terms of ore shoots. Determination of the reasons for ore localization may be difficult where the ore minerals deposited separately from those of the gangue. Such a relatively tiny volume of ore minerals, especially precious-metal minerals, need be added to country rock or gangue to make it ore that the agencies providing the trivial openings needed may leave no discernible traces behind them. Hulin[4] emphasized this in contrasting signs of localization of precious-metal with those of base-metal deposits.

A near coincidence of distribution of gangue and ore suggests that they deposited together, by the mere fact of their close association. With an appreciable time interval between the entry of the one and that of the other, conditions of fracture permeability might be expected to change during the interval. The later solutions would be forced to use new channels and to deposit vein matter in new places. The distribution of the bulk of the gangue would differ from that of the ore. Hence, if it does not it is likely that gangue and ore came in together.

But in spite of coincident distribution of gangue and ore minerals one might have followed the other, after an interval long or short, using the same channels and depositing in the same places. To decide whether gangue and ore deposited together or at different times, field criteria may lie in the vein structure and the sequence of vein-mineral deposition. If the vein lacks intermineral brecciation, and the simplicity of the vein composition suggests a single surge of mineralization, it is reasonable to suppose that gangue and ore came in together.

If, on the contrary, polished-surface relations or other features suggest a definite time interval between deposition of the gangue and that of the ore minerals, we are forced to explain why, despite the time interval, gangue and ore minerals used the same channels and deposited in the same places. The case is not uncommon and warrants some discussion. Three explanations may be thought of, for our case of coincident gangue and ore distribution with a sharp break-off between deposition of the gangue and that of the ore minerals:

a. Conditions favoring vein formation prevailed continuously, and, within the general area where ore shoots occur, openings formed at the right time. The vein matter came in discrete surges, the last surge carrying all the ore minerals and very little gangue.

b. The vein matter was brought by continuous flow of solutions changing progressively in composition from barren gangue minerals to practically pure ore minerals. The observed break-off between gangue deposition and that of ore minerals resulted from a temporary cessation of conditions conducive to deposition at the place discussed.

c. Both the supply of vein matter and the conditions favoring its deposition were intermittent.

Explanations *a*, *b* and *c* may have different meanings in terms of ore. If conditions for deposition were not persistently favorable throughout the time of vein formation, and if the ore minerals came in a sudden, brief surge, a nice coincidence is needed between the existence of conditions favorable for deposition and the presence in the vicinity of the ore-bearing solutions. This coincidence might be expected to be lacking with many veins of the district; a number of mining camps show but one or two productive veins out of a multitude.

In contrast, solutions continuous in flow and changing progressively from waste to ore could arrive within wide time limits and still deposit, with conditions persistently favorable toward deposition. Where conditions were only intermittently favorable for deposition, but the solutions came in continuously, chances for ore may still be better than where both favorable conditions for deposition and the flow of solutions were intermittent, for some ore, even if low-grade, would be in the vicinity ready to deposit throughout a considerable proportion of the period of mineralization, and its chance of catching favorable conditions for deposition would be greater than that of ore minerals arriving in one swift surge.

To determine the most likely of the three possible explanations for coextensive gangue and ore and a break-off between the deposition of the two, we turn to other field facts and their corresponding inferences. These facts must bear on the two unknowns in the problem: (1) the persistence or nonpersistence of conditions favorable for deposition, and (2) the continuous or intermittent nature of flow of the vein-forming solutions. Whatever facts are found, note the interrelation of the two sets of facts: if one set indicates intermittent conditions favorable for deposition, the other set may point to either a continuous or a jerky flow of the solutions; but if one set indicates persistently favorable conditions for deposition, the other set must show that the solutions came in separate surges, the first depositing gangue and the second ore; otherwise the two sets of facts are in conflict, and the break-off between deposition of gangue and that of ore is not explained.

The discussion might be extended to include the more common case of decidedly wider-spread distribution of gangue than of ore shoots, and the various implications this fact may carry with it. Gangue-ore distribution is an important feature of vein morphology.

3. *Localization of Gangue and Ore.*—Reasons for the formation of gangue and ore bodies at the places where they are found are often suggested on geologic projections by the association of such bodies with certain features of the vein morphology. A few examples from the field will be given.

The gangue or ore may have formed in a segment of the vein bounded by sharp flexures in the vein surface. If the vein fracture suffered differential movement of its walls in a manner calculated to make an opening where we now find the ore, it is a reasonable inference that the opening was made in this manner, prior to or during the time of vein formation. But to be sure, we must ascertain the period of the faulting; if it happens to be post-mineral, it could not have localized the ore; the location of the shoot is a coincidence. There would be no incentive to explore other similar vein segments. If, however, the time of the faulting fitted the theory of localization, there would be every incentive for exploring segments similar to the one that provides the setting for the discovered ore shoot.

The gangue body or ore shoot, or both, may be localized at the junction of the vein with an acute-angle branch. It may be supposed that shattering of the enclosed wedge provided the necessary openings. Examination of the wedge may confirm this notion, and study of the vein morphology may show that other acute-angle intersections, where the country rock was not shattered, localized no ore shoots. Also, it might be found that shattering of the rock forms ore shoots at acute-angle junctions only. This would lead to search for another function of an acute-angle branch beyond mere rock shattering. Perhaps distribution of gangue or ore shows that such junctions formed channelways up which the vein-forming solutions ascended, and that widespread shattering with accompanying diminution of pressure and temperature was needed for deposition of ore minerals.

The absence of control by any visible features on the geologic projection may be as significant as its presence. The lack of control by one such feature, wall rocks, has been described in the field example cited to illustrate the criteria of hydrothermal alteration, orientation of the vein fractures, and wall-rock control (p. 100). In this case minor strike faulting on the north-south veins, the ore shoots of which disregard wall-rock formations, formed wide and rich veins in wall rock unfavorable with the east-west veins. But here the process of growth by accretion during intermineral strike faulting left behind it traces in the sheeted and brecciated vein structure, and the multiple generations of certain vein minerals. In perhaps more numerous cases, no ore or gangue control whatever is discernible upon a geologic projection, or at best but unsatisfactory hints. To explain an ore shoot in such a case, and perhaps find others, we must surely turn from local study and look about us.

Some of these baffling occurrences may be explained by a certain type of regional stress active at the time of vein formation. Ore or gangue may be localized without obvious evidence for the localizing agencies if at the time of vein formation the fracture walls opened as one opens an envelope. The comparison may be fair, because one may squeeze an envelope open or pull its front and back apart. Fissures may very likely be opened in either of the two ways. Some at Baguio, P. I., seem to have been squeezed open, while others, at Pachuca, Mexico, appear to have had their walls pulled apart.

Where such opening took place at the time of mineralization brecciation of the wall rock or of early vein minerals is usually not evident, nor is it necessary in the process. Frequently one sees only an irregular, unsymmetric vein banding, caused by older vein matter being torn in two longitudinally or pulled away from one or the other wall, and the resulting tabular opening being sealed by additional vein matter.

With no control of deposition apparent on the geologic projection, we may appeal to such mechanics as a working hypothesis. To test it, field facts with their inferences are sought. Two such criteria used at Pachuca to support the idea of intermineral pull normal to fracture walls come to mind.

The first criterion was furnished by a wide quartz-porphyry dike, striking parallel to the veins in question but dipping more steeply. Regional study showed that the dike was a member of a family of which the members emplaced themselves at a time nearly coincident with that of vein formation. At one place the walls of this dike are quartz-latite showing nearly horizontal well-developed delicate flow layers arranged in gentle crenulations. This flow-banding extends right up to the dike margins (which are entirely clear-cut) with not the least evidence of crumpling, although the banding is so nearly like thin bedding that the rock would tend to fold like a thin-bedded sediment if subjected to horizontal compression. The dike, a porcelainlike rock, shows no sign of assimilation of its wall rocks. The inference is that the dike exerted no pushing on its walls; the latter were being pulled apart, or at least held apart, as the dike entered its fissure.

If an active tensional stress existed at the time of dike intrusion, it acted about normal to the dike walls; i.e., perpendicular to the strike of the dike and certain veins, and roughly horizontal. After the notion of such tension had been entertained, it became at once clear that variations in attitude and mineralization of one of these veins fitted the theory. The vein is a thrust, in places as flat as 15°. In the stretches of very low dip the thrust is nearly unmineralized. It forms a wide vein, however, where it dips 40° or more. Complex drag of the flow-banding in the wall rocks suggests that normal movement, down the dip of the thrust, succeeded the initial, reverse movement. Normal movements on a fault dipping 15° over long stretches demand a pull distinct from gravity. A pull in the direction inferred from study of the dike wall rocks—i.e., perpendicular to the strike of the dike and the vein in question and roughly horizontal—would pull apart the walls of the vein fracture where the dip is steepest. This would explain the width of the vein at such places. The same pull would also induce the dip-faulting that succeeded the thrusting. But the opening of walls is fissuring such as forms gash joints, while the dip-faulting is shear. The two processes could scarcely have gone on simultaneously. Field facts must provide the explanation.

No post-mineral gouge appears in the vein, and little gouge anywhere. This indicates: (1) that the normal faulting was accompanied by strong tensional pull that prevented attrition, checking a supposition derived from other facts; (2) that the slipping occurred prior to the mineralization. The change from slipping to pulling apart could have been coincident with the start of mineralization. Here a new inference is brought in to explain field facts used in testing an earlier inference. It seems likely that the vein matter managed to enter the tensional fault, sealed it, destroyed the lubrication and changed the fault from a plane of ready shearing to a mere zone of weakness. The tension tore open this zone, so that the vein shows the crude banding described as characteristic of veins formed during the pulling apart of their walls. Such a vague hint as this crude banding, however, would not suffice in itself as a criterion of vein origin.

Turning to the barren portions of the vein, the pull suggested would open but slightly the vein fracture where the latter, because of its flat dip, lies so nearly parallel to the tensional direction.

CONCLUSION

Criteria exist in nearly every camp that indicate whether a vein may be productive or not, and point to the location of ore shoots in productive veins. But such diagnostic features may never be used, even between one vein and its nearest neighbor, with perfect safety. Listing criteria of observation with no regard to the causes behind them is fraught with deception. The use of such criteria must go hand in hand with complete study of a district, and, in particular, the exact deciphering of the geologic history of the events that took place at or near the crucial epoch for any mining district, the period of mineralization.

We must continue the systematic collection of data on vein morphology, and make a genuine effort to correlate these data. Above all, we must try to infuse life into the dead factual mass, so that it may act to serve our end, the finding of ore. The vital spark needed lies in the causes back of the empirical facts discovered. So far we have been stubbing our toes on "hard facts"—hard because their meaning is not understood.

ACKNOWLEDGMENTS

I am indebted to Prof. C. A. Anderson, of the University of California, for helpful criticism. To those interested in the fundamentals of scientific thinking I can recommend no better guide than the stimulating paper by Douglas Johnson[5] on the role of analysis in scientific investi-

gation. The present paper is largely an attempt to apply to the field of mining geology the principles set forth by Johnson.

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DISCUSSION

[Discussion of this paper appears on page 426.]

Some Observations in Ore Search

SYMPOSIUM

L. C. GRATON presiding

(New York Meeting, February 1938)

CONTENTS

PAGE
INTRODUCTION AND ACKNOWLEDGMENTS. By George M. Fowler. 2

Question 1—Is Structural Deformation of Some Character Always Necessary for the Migration of Mineralizing Solutions, Especially in Limestone or Other Dense Rock?

DISCUSSION by:

A. M. Bateman 120
C. H. Behre, Jr. 118, 123
T. M. Broderick. 121
R. H. Clarke 123
J. D. Forrester for M. H. Gidel . . 114
G. M. Fowler 112, 116, 121
L. C. Graton 121
R. D. Hoffman 120
I. B. Joralemon 121
S. F. Kelly 125
G. B. Langford 123
H. E. McKinstry 116
D. H. McLaughlin 118
W. H. Newhouse 123
R. H. Sales. 116
Edward Sampson. 122
J. S. Stevenson. 117
L. B. Wright. 112

Question 2—What Are Some of the Chemical and Physical Characteristics in Certain Beds within a Limestone Formation that Determine Their Favorable or Unfavorable Aspects as Reservoirs for Ore and Other Introduced Minerals?

DISCUSSION by:

G. W. Bain 127
C. H. Behre, Jr. 131
J. S. Brown 126
E. L. Bruce 129
R. H. Clarke 130
G. M. Fowler. 131
L. C. Graton. 128
G. F. Loughlin 128
R. H. Sales. 129
A. K. Snelgrove. 130

Question 3—Are There Any Criteria by Which One Can Determine When Mining Operations Have Reached the Roots of an Ore Deposit?

DISCUSSION by:

J. M. Boutwell 139
T. M. Broderick 138
E. Y. Dougherty 137
G. M. Fowler. 132
I. B. Joralemon. 132
G. B. Langford 139
G. F. Loughlin. 135
R. H. Sales 134
F. A. Thomson 136
Edward Wisser. 140

General

S. F. Kelly 145
References 146

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Introduction and Acknowledgments

By George M. Fowler*

This symposium is the result of an effort to correlate the discussions presented on the Mining Geology program on Feb. 16, 1938, at New York.

As Chairman of the Committee on Mining Geology from February 1934 to February 1938, the writer felt that the program would be especially interesting if it was centered around a few questions of essential interest to the group. Accordingly, a list of possible questions for discussion was submitted to the members of the Committee on Mining Geology with the request that three be chosen. These three questions formed the basis for the symposium. Those participating were requested to submit factual evidence from their own observations. The oral discussions recorded at the meeting by a stenotypist were augmented by written discussions and the combined material was edited and arranged.

The assistance of many friends is gratefully acknowledged. L. B. Wright, John S. Brown and I. B. Joralemon led the discussions regarding Questions 1, 2, and 3, respectively. L. C. Graton presided as Chairman at the symposium. C. H. Behre, Jr., M. H. Gidel, E. S. Moore, A. O. Hayes, and others critically read the recorded oral data and their suggestions have been followed in the preparation of this manuscript.

Question 1.—Is Structural Deformation of Some Character Always Necessary for the Migration of Mineralizing Solutions, Especially in Limestone or Other Dense Rock?

Discussions

George M. Fowler

The intended definition for "dense" in this question was the common one: "Having its parts crowded closely together; compact in structure," instead of the less common meaning "heavy." A more appropriate selection of words should have been made. Dr. A. O. Hayes, Professor of Geology at Rutgers University, suggests "close-grained" or "impervious" instead of "dense," and I concur in his suggestion.

Lawrence B. Wright†

It may be helpful to scrutinize the question first and then review some of the factors that usually govern mineralization, with attention focused on the way in which these factors might affect a type case. Some examples of occurrences, which have been observed and which may bear on this topic, will be mentioned.

The question as stated implies that structural deformation customarily precedes mineralization, but it is desired to determine whether this is always true and whether such deformation is required for metal deposition.

A dense rock, such as limestone, is taken as the approximate type of host to be considered. According to the wording of the question a highly permeable rock such as loosely consolidated sandstone would not be considered a "close-grained rock." Its permeability might even exceed that of a very close-grained but structurally deformed rock. Therefore, it seems that the question narrows to a consideration of the attack of mineralizing solutions on a relatively impermeable but chemically amenable host. If this be the proper conception of the problem to be discussed, the chief factors entering into the behavior of the mineralizer should be considered. It will be assumed for the purpose of this discussion that the mineralizing solutions are abundant and will suffice to the limits of permeability, or to complete replacement of the host rock to the limits of final deposition, and that no extraneous factor cuts off the supply of solutions during the process.

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Ascending solutions of magmatic origin are generally conceded to be under influences of greater pressures and higher temperatures than those of superficial origin. Conceivably the two types of solution could in some cases be similar in composition, but progressing in their work of wall-rock attack at different rates. The hypogene solution would accomplish the same end in less time than a supergene solution of similar composition. The time factor involved in effecting a definite replacement may be a function of and related to the temperature-pressure factor. Also, where solutions that come into contact with amenable host rock lack the required temperature-pressure-time condition, little or no replacement may result.

Permeability should be considered as an important factor, even though dense rocks are under discussion. The whole story of mineral deposition in a dense rock, even under the set of conditions prescribed in our question, probably should not be limited to geochemical considerations, as pictured under surface temperatures and pressures. Under sufficient pressure, solutions are conceivably forced along the submicroscopic crystal margins and even along the cleavage planes. Familiar to all are photomicrographs showing replacements of metallic substances, such as galena, by material introduced along crystallographic cleavages. G. M. Schwartz[1] pointed out that this may be accomplished by supergene solutions as well as hypogene, citing and illustrating a number of examples.

To what extent these interchannelways have previously been emphasized by slight deformation is difficult of determination, but in some cases where the crystal appears not to have been distorted or shattered the suspicion is strong that the solutions effecting replacement did so through crystallographic channelways. This may have required considerable solution pressure, and had such pressure been of less intensity, emplacement of the invading mineral might not have been possible. It would seem therefore that there is a definite relationship between permeability and solution pressure, which must be suitably in effect at the time of any replacement in a dense host rock.

The common conception is that where a considerable amount of calcareous rock has been replaced by such a mineral as galena, an attack along the walls of a vein during mineralization requires no actual penetration during the process of metasomatism; the widening of the deposit is effected molecularly and the final width determined by the limit of solution supply or limit of host rock. Is not this mode of ore deposition a magnified example of solutions penetrating the cleavages of a single crystal of, say, galena? In each case an opening suitable for passage of solutions is required and the width of replacement (extent of digestion of wall material) is determined by factors common to both the minute and large events. If so, then the beginning of replacement in either case requires that a channelway be provided, although the important part of the process following be wholly geochemical.

As indicated above, I do not think it always essential that the channelway for mineralization be provided by actual deformation. Barren solutions preceding mineralization may attack the host rock with a conditioning effect. Premineral alteration of the invaded rocks or minerals by hydrothermal solutions may account for some of the large disseminated ore deposits in dense plutonic rocks. Premineral conditioning of limestone by circulation of barren solutions may take the form of open cavities and channelways. These may later determine the locus of ore deposition.

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[1] References are on page 146.

Another question to be considered is: Is it possible for a crystalline rock to remain structurally dense and unstrained? What may appear as a dense rock, even microscopically, is a portion of some larger mass. What large mass of rocks bearing ore deposits has not been subjected to considerable stress? While major forces are dissipated along fault planes, in block movements and in folding, does not each particle of the mass record some effect of regional deformation?

Isolated crystals of later feldspar are common in the Keewatin lavas of Ontario; of scheelite in hydrothermally altered pre-Cambrian rocks near Cochise, Arizona; and of auriferous arsenopyrite in dense quartzite in western Ontario. Other examples could be given. Each of these might be considered a miniature mineral deposit. The material of which they are composed reached its location through some channelway and attained its ultimate dimensions by chemical processes.

While the foregoing observations and remarks do no more than open the door to further discussion, it is hoped that a better understanding of the subject will result. My conclusion at this point is that structural deformation is usually present in a dense rock, plays an important part in the migration of mineralizing solutions, and therefore is a necessary adjunct to mineralization.

J. D. FORRESTER*

This discussion is given at the specific request of Mr. M. H. Gidel, Assistant Chief Geologist of the Anaconda Copper Mining Co. The views expressed are largely the outgrowth of his experienced studies.

A physical factor that has been little considered in the formation of ore deposits, but which, in many instances, appears to be as important as fissuring and shearing developed by structural deformation, is the occurrence of an impervious, perhaps resilient, confining medium or "blanket." Such a condition would constitute a restriction to mineralizing channelways and thereby retard or impound migrating solutions and permit more time for mineral replacement of favorable rocks and for the precipitation of sulphide and other mineral crystalloids, including silica-gel accumulations. This would greatly increase the relative volume of such deposition. Restricted or diverted channels in tighter rocks would tend locally to maintain or increase the pressures of passing solutions and, in effect, maintain or increase temperatures. This, in conjunction with the important factor of time, would favor heavier deposition of mineral compounds. As an example of such a phenomenon, the Tri-State district may be cited. Here the impervious, resilient Cherokee shale overlies the fractured magnesium-bearing limestone or dolomite beds that contain the commercial zinc-lead ore bodies, and has resulted in mineral deposition of considerable volume, confined largely to certain horizons in the Boone formation, and over an extensive area. This thick and practically unbroken "blanket" of Cherokee shale overlying the more brittle, sheared and mineralized Boone strata probably controlled the development of solution channels and cavities along the fracture pattern in the harder, more easily fractured strata. Subsequent deposition of sphalerite, galena, marcasite, quartz and later carbonate minerals was delimited by the impounding effect imposed on circulating solutions by the overlying shale.

The cementing by sulphides of angular quartz fragments into an "ore breccia" is a common occurrence in Tri-State ore bodies. This implies that partial suspension or support of the fragments occurred originally in a sludgelike precipitate or crystalloid mixture of zinc and lead sulphides. The angular quartz fragments probably resulted from the falling and breaking up of the insoluble chert nodules in the caverns, which, according to many authors, were first formed by water or solutions migrating through and enlarging the channelways in the chert-bearing dolomite. It is conceivable that such crystalloid sludges in quantity could "intrude " along a fissure, which, under high hydrostatic pressure and restricted "blanketed" conditions, ultimately would become consolidated and more coarsely crystalline with the passing of time. Such a crystalloid sludge might truly be an "ore magma."

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"Free flowing" hot or cold springs rarely deposit any ore minerals in commercial quantities. Only the surface phenomena connected therewith can be observed, but the relatively small amount of mineral salts present in the solutions is impressive. It is possible, of course, that such flowing spring water is "tailing" water from a heavier deposition of minerals in the channelways at depth. The hot springs at Mammoth, in Yellowstone National Park, are depositing a considerable quantity of calcium carbonate, presumably derived from the near-by Madison limestone. Springs of this type can be classed as "free flowing"; that is, with a more or less direct exit to the surface.

Another occurrence in which an impounding medium appears to have been present and partly responsible for the localization of ore mineralization is that of the large zinc-lead ore deposits of Upper Silesia. Here the wurtzite, sphalerite, galena and marcasite ore occurs as a replacement of dolomite in portions of a flat geosyncline. The bottom of the "ore bed" rests on a layer of impervious, soft shale or mudstone (*vitrioletten*). The shale has been the bottom delimiting or controlling factor for migrating mineral-bearing solutions, which traveled along joints and minor fractures in the blocky dolomite, and along subsurface undulations or shallow channel areas within the major structure. In this extensive ore deposit, the occurrence of heavy sulphide deposition in dolomite again emphasizes the fact that magnesium-bearing rocks appear to be particularly favorable for sulphide replacement.

The idea of a controlling or impounding factor also appears tenable in numerous other cases of commercial mineral occurrences, especially in radial fissure-vein systems that are near and related to intrusions or cupolas of igneous rocks. To some extent such impounding conditions are analogous to those controlling the migration of gas and oil "differentiates" that are collected and concentrated in favorable structures, such as domes. An ideal example of this condition is at the old Custer mine and adjacent gold properties near Winston, Mont. Here an isolated cupola of granite porphyry, 2000 by 1200 ft. in areal extent, was intruded into an older andesite. The parallel system of larger veins, which extend across the cupola and into the andesite for 2000 ft. or more, were all productive, within limited distances of the granite porphyry.

Confining rocks like shale and hornstone apparently control the channelways for varying hydrothermal mineral deposition in contact zones.

The covering of older formations, into which the intrusive lobes of an igneous rock penetrate, may be sedimentary or early igneous in type. The degree of density and imperviousness of the cover would proportionately retard the migration of solutions rising from below, and thus would facilitate deposition in any more favorable so-called "host rock" lying beneath. For example, some major impounding medium, which has been subsequently eroded, may have affected the ore deposition and vein systems in the Butte (Summit Valley) district. A study of the restoration of blocks of ground along large fault displacements in the district permits the postulation of an old terrain probably 2000 to 3000 ft. higher than the present surface. Within these blocks of ground there occurred, in the upper portions, an aplite differentiate beneath an uplifted cover of sedimentary rocks. Roof pendants of sediments and of older andesite, which occur at various localities over the Boulder Batholith, substantiate this postulation.

Such an impounding condition for ascending mineral-bearing solutions would result in more extensive alteration of rocks in a highly fractured area and would facilitate and account for the deposition of minerals in zonal arrangement, a common feature in many of the larger mining districts.

The vein system and the ore deposits of the Marysville district, north of Helena, Mont., suggest the existence of impounding conditions during the period of mineralizing activity. The resulting greater time interval for mineralization probably permitted more mixing and slower cooling of rising solutions and hence the deposition of relatively greater volumes of commercial minerals in a zonal arrangement within the fissure systems. Incidentally, the Marysville granite batholith intruded the limestone and shale formations that comprise the Belt series.

This discussion is not intended to minimize the importance of structural deformation in rocks or the chemical and physical characteristics of rock formations favorable for mineral deposition, but to present an important factor undoubtedly responsible for much local zoning or heavier deposition of minerals in fissures and shear zones.

George M. Fowler

Amplifying Dr. Forrester's remarks, few of the ore deposits in the Tri-State mining district are found in actual contact with the thick shale beds, Cherokee or Chester, that overly them but the importance of an impervious covering seems evident, particularly in the Oklahoma-Kansas part of the district. There the highest part of most of the ore bodies is 50 ft. or more below the bottom of the shale. The immediate covering in many cases is massive, tight limestone and chert beds in the upper part of the Boone formation, which probably would retard the mineralizing solutions as suggested by Mr. Gidel.

H. E. McKinstry*

Damming of ore solutions by constriction or obstruction of channelways is often cited as an influence favorable to ore deposition. It seems to me that one should distinguish between two types of damming. The first is the confining or impounding of solutions, preventing their free circulation. This is analogous to a storage reservoir in a water system. The second is the diversion or channelizing of solutions by a barrier. This is analogous to a diversion dam in a stream that locally *accelerates* the flow.

Now, while suspended sediments deposit more rapidly from still water than from flowing water, it should be borne in mind that deposition of *dissolved* material is not necessarily favored by impeded circulation. In fact, if chemical reaction plays a part in deposition, this is facilitated by rapid renewal of pregnant solution and prompt removal of the products of reaction. Even if deposition is due to cooling, it is clear that the cooling effect of a given area of wall rock is greater if it acts on a freshly supplied hot solution.

Our habit of visualizing ore bodies in cross section often suggests that an impermeable horizon or constriction has impeded the flow of solution, whereas when we come to consider the third dimension we may see that it has merely diverted or channelized it. An impermeable zone may therefore act as a dam, but the conclusion that it has caused ore deposition by impeding the circulation does not necessarily follow.

Reno H. Sales†

The penetrability of a rock to solutions depends primarily upon its permeability. Commonly we may observe in dense limestones ore replacements that have resulted from the action of mineralizing solutions. From my own experience in the field I am led to believe that mineral solutions gain entrance to dense rock masses mainly through the medium of fissures, bedding planes or other openings. If the nature of the solution is such that the host rock undergoes chemical change, slow invasion outward from existing channels may result in replacement deposits. The impenetrability of certain rocks, such as shales, limestones, or even hard sandstones, to chemically inert solutions is illustrated in many of the deep California oil pools where water, oil and gas, under pressures of more than 3000 lb. per sq. in., are trapped by shales or low-porosity sand members.

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We may also observe rocks, structurally deformed to a high degree, with little or no development of porosity; in fact the reverse is not uncommon. Highly folded massive limestones may become less porous through recrystallization. Similarly, sandstones through crustal movements are converted into dense quartzites. On the other hand, very slight folding causes channels for the passage of solutions in relatively impervious rocks. With thick, massive beds the fracturing may be very irregular and frequently at steep angles to the dip. In thinly bedded limestones, for example, the necessary adjustment may be chiefly along bedding planes with cross fracturing playing a minor role, as in the ore-bearing limestones of the Tri-State zinc-lead district.

If by "structural deformation" is meant the development of fissures, joints, fractures, bedding planes, adjustments, or other channels through which a mineralizing solution may gain access to a dense rock mass, my answer to our question is "yes." Natural porosity plays a minor part in the migration of solutions through dense rocks.

JOHN S. STEVENSON*

The writer wishes to submit the pertinent features of one deposit within a massive hornfels in which structural deformation, as manifested by joints and shears, was necessary for the migration of mineralizing solutions.

Migration of Mineralizing Solutions at the Privateer Mine, B. C.

The Privateer mine is in British Columbia's youngest gold area, the Zeballos area on the west coast of Vancouver Island. The deposit (as of 1937) is a quartz-sulphide fissure vein from which spectacular high-grade shipments of gold ore have been made. For the most part the vein traverses a dense, massive hornfels, but it has cut a tongue of quartz diorite 210 ft. wide and is striking toward a large batholithic mass of quartz diorite lying less than 1000 ft. ahead. The vein filling consists of abundant sulphides and gold in a quartz gangue. The paragenesis of these minerals is as follows: pyrrhotite, early quartz, pyrite, arsenopyrite, later quartz, sphalerite, chalcopyrite, galena, native gold, carbonate and marcasite.

The features of the deposit relating it to the current discussion are: (1) the control of the movement of the early hydrothermal solutions outward from the main fissure by joint planes within the dense hornfels, (2) the ingress of the later gold-bearing solutions into fractured vein matter of earlier deposition, (3) the restriction of the gold values to the vein fissure. Had migration, without structural control, been a possibility, some of the gold from these rich solutions would have migrated.

The escape of the earliest hydrothermal solutions from the main fissure was controlled by diversely oriented joint planes within the hornfels, joint planes that antedated the vein fissure. The effect of these hydrothermal solutions on the hornfels has been conspicuous. The solutions developed narrow zones of bleaching in which the alteration spread outward from either a central plane or a quartz-pyrite stringer for ¼ to 2 in. on either side, the central plane or quartz stringer indicating the site of an earlier joint plane. These narrow buff-colored zones of bleaching, spaced from a few inches to several feet apart, contrast markedly with the dark grayish color of the intervening, unaltered hornfels. Although not observed in the section of the quartz diorite cut by the Privateer adit, similar alteration of quartz diorite outward from fissures and joint planes is a feature of other deposits in the area.

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Since migration of the later gold-bearing solutions into the wall rock has been only along branch fissures from the main vein it would appear that the early solutions in the Privateer deposit sealed all available joint planes.

Returning to the main vein, it is seen that much of the early vein matter was intensely fractured, and the openings so created served to guide, or were filled by, the later, mineralizing solutions. A study of polished sections of the ore shows that much of the early pyrite and arsenopyrite has been broken into angular, largely uncorroded fragments, and the aggregate sealed by the later minerals, which comprised quartz, sphalerite, chalcopyrite, galena and gold. The prevalent angular uncorroded shape of the pyrite and arsenopyrite fragments indicates that filling of intervening open spaces, as contrasted with replacement of solid material, has been the predominant process in this later vein mineralization. If replacement had been important here, most of the contacts between the later minerals and the unreplaced fragments of the earlier minerals would have been the usual smooth, "mutual" contacts typical of such replacement. It is evident, then, that within the vein itself the movement of later mineralizing solutions was controlled by intermineralization fracturing.

The last and the most conspicuous feature of the Privateer, relative to the general discussion, is that, despite the extremely high gold content of much of the vein matter, none of it has seeped or migrated into the wall rock. Assays of wall-rock samples run only traces and *nils* in gold. A concept of the high gold concentration of some of the vein solutions may be gained from the fact that one exceptionally high-grade section of the vein, 110 ft. long, and averaging 9 in. wide, produced 43.177 tons of ore averaging 10.8 oz. gold per ton. The only migration of such mineral solutions has been along branch fissures, where similar high-grade vein matter is found. Assays of rock immediately adjacent to either the parent or branch veins show traces only of gold; there is no evidence whatsoever that these extremely rich solutions, as such, have seeped into the massive wall rock.

C. H. BEHRE, JR.*

In brief, mineralization could not penetrate far or freely into the hornfels. It was confined to the portion of the country rock that was near a fracture. For mineralization in economic quantity to be localized and made effective, structural deformation was clearly necessary.

D. H. MCLAUGHLIN†

In searching for an example of a major mining district in which structural deformation had little to do with the localization of the ore deposits, the Witwatersrand surely would be one of the few that would come to the minds of many geologists, yet I venture to suggest that even there the folding of the beds and fracturing along specific horizons may have played a more important part than is generally recognized.

Neither of the two prevailing concepts of origin of the gold ores—viz., the placer theory or the infiltration theory—has made more than nominal demands upon structural geology. The placerists believe the gold was concentrated mechanically with the quartz pebbles of the reefs but admit that it was later dissolved and reprecipitated in its present finely divided form. Apart from association between abundance of gold and various characteristics of the conglomerates, the only structural features that seem of practical importance to advocates of this theory are those that determine the loci of the particular gold-bearing sedimentary horizons. The infiltrationists, on the other hand might logically be interested as well in all structural conditions that could have influenced the movement of metalliferous solutions through the rocks, but so far they have paid little attention to anything except the relatively higher permeability of the coarser sediments as an explanation of the persistent and close association of gold with certain beds of conglomerate.

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During a short visit on the Rand a few years ago, I was impressed at many widely separated places in the district by signs of fracturing that could be detected along or close to the ore-bearing horizons. On certain reefs, a well-defined break along the contact between conglomerate and quartzite (or slate) appears to be a persistent feature; and in a number of places a pattern of en echelon fractures is revealed by successions of short, oblique quartz veins either in the hanging wall or footwall. Indeed, in certain mines, the bedding crack continues even where conglomerate is missing and serves as a marker by which the horizon can be followed. Rock alteration, pyrite, and other signs of mineralization usually can be seen along such breaks, and even gold has been found on them; though rarely, I believe, in sufficient quantity to permit stoping beyond the limits of the conglomerate. The pyritic quartzite ore in certain zones along the reef horizons where pebbles are missing may possibly be attributed to replacement along bedding cracks of this sort, now obliterated by the mineralization, but my acquaintance with the field is surely too limited for me to attempt to review the evidence on this interesting point.

I should, however, like to suggest the possibility that in the deformation of the region differential movements between the layers of the thick Witwatersrand series not only caused drag folds in the incompetent members such as the so-called distorted bed, but also resulted in persistent cracks parallel to the bedding in the brittle rocks or in zones of oblique cracks en echelon to it. Fracturing of this sort would tend to be localized by physical discontinuities, such as the conglomerate layers in the quartzite, and might well have much to do with making specific horizons of these rocks more permeable than others, or in creating belts of locally higher permeability within broad areas of a particular conglomerate bed. Changes in attitude of the bedding along transverse minor folds or along bends in strike or dip would probably modify the intensity and quality of minor fracturing of this type and thereby result in differences in relative permeability along such structures which might have marked influence on the flow of solutions through rock.

As far as I know, no efforts have been made by the Rand geologists to correlate structural details of the sort mentioned above with abundance of gold.* In a few places, striking irregularities in structure appear to coincide with abrupt changes in grade and thickness of ore, but very careful studies based on the voluminous statistical data and on careful recording of fractures on maps and plotting of minor variations in attitude of the reef would have to be made before the question is settled.

Interest in the possible influence of these structural features should not, I think, be confined to the advocates of the infiltration theory, for the placerists themselves depend upon migration of solutions to explain certain distinctive features, such as the absence of black sands and the abundance of pyrite (involving introduction of quantities of sulphur far in excess of the gold in the reefs) as well as the local redistribution of gold. In such processes, gold must pass through a mobile state and be capable of migration to the extent that impoverishment in one place and concentration in another might be brought about by movement of active solutions along courses determined, in part, at least, by the structural details under consideration.

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* Since these comments were made, a most interesting paper by Dr. David Kransdorf[2] has come to my attention, in which it is stated that payable reefs in that property have well developed partings, usually on the footwall, whereas unpayable reefs are "frozen" to the walls, and that the "pencil line contact" of the Randfontein Leader may contain sufficient gold to be minable even where pebbles have disappeared. Both of these observations and other data in the paper strongly support the thesis that a relationship exists between distribution of gold and fracturing along the bedding.

No one with the least familiarity with the Rand can, of course, fail to recognize that the close association that exists between the gold and specific beds of conglomerate (and with many of the textural details of these interesting rocks) is the outstanding geologic feature of the ore bodies of the region, but possibly, in depending too exclusively on this relationship, the mining geologists of this great field are neglecting various minor structural controls that are capable of being of very great practical service in their efforts to predict the location of ore shoots and of lean zones or to appraise percentage payability of the reef in advance of development.

A couple of years ago in a short note in *Economic Geology*, F. E. Keep[3] expressed his approval of "leaving the controversy regarding the origin of the gold deposits of the Witwatersrand to those who have had sufficient experience to be able to speak with authority." Surely no one who possesses the familiarity with a particular ore deposit that comes of long continued work on the staff of a mining company will fail to share his implied impatience with publication of hasty observations of visitors; but comments and discussion on the part of the geological profession on the extraordinarily interesting problems of the Rand are as inevitable and as proper as criticism in the field of literature and art. They seem especially pertinent where unsettled major controversies exist and where to an outsider some promising lines of attack appear to have been neglected.

It seems to me to be very probable that even on the Rand the answer to a number of puzzling questions concerning distribution of gold will be found when the current concepts that dominate geological thought concerning origin of the deposits are supplemented with more precise understanding of the influence of some of the structural complexities on distribution of gold.

ALAN M. BATEMAN*

I should like to take up the first question for discussion and twist it around backward, and say instead, "Can anyone here tell me of *any* fair-sized or large-sized deposit, in which workings are sufficiently numerous to disclose the enclosing and surrounding rocks, that has been formed without dependence upon fractures or other structural deformation?" In other words, to stir you up, I defy you one and all to tell me of any medium-sized to large-sized deposit that has not been localized by some kind of structural control.

ROBERT D. HOFFMAN†

In answer to Dr. Bateman's challenge, I may say that I know of at least one deposit that is not related to any fracture or fault; i.e., the Vlakfontein nickel deposit found in the Bushveld Complex, Transvaal, South Africa. Here are a number of small breccia pipes of pyrrhotite occurring in massive norite. These pipes vary from 15 to 30 ft. in diameter. There are no fractures leading out from any of these deposits, nor any faults traceable on the surface. There has been sufficient mining to delimit each little pipe. Elliptical drifts have been driven around the outline of the ore bodies, and in none of these drifts is there any trace of a fracture or fault.

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T. M. Broderick*

The Calumet conglomerate has produced about four billion pounds of copper and at the bottom of the mine the copper mineralization is still going down, although it is not rich enough to be mined at a profit at present prices. The deposit ranks as one of the world's great ore bodies. In the 9000 ft. down the dip that it has been worked, no fissured or shattered zones that have any appearance of having introduced the copper-bearing solutions have come to light. The conglomerate itself seems to have been the solution channel to the depth of observation. However, I will admit that we believe that probably at much greater depths the solutions were brought into the conglomerate through a broken or fissured zone of some sort.

Ira B. Joralemon†

I think that Alan Bateman also kept his foot in the door because at the end of what he said he changed "structural deformation" to "structural control," and in the examples given I think that structural conditions were responsible for the ore. For instance, in Calumet, certain beds are replaced and a change from one bed to another might be the structural condition. The same might apply at Mesabi, so I think "deformation" was a poor word to use in the original question. If it is replaced by "structural conditions" I do not believe that anyone can controvert Alan Bateman.

I agree with those who say that structural deformation is not always necessary, although structural control, of course, is.

George M. Fowler

I believe that structural deformation of some character is always necessary for the migration of mineralizing solutions in almost any dense or close-grained rock. In the Tri-State and other mining districts I have noted that ore is found only in zones of deformation. Between these zones introduced mineralization is absent, indicating that it impregnated the limestone only a few feet beyond the disturbed zone. These conditions seem to control in both coarse-grained and fine-grained limestone.

L. C. Graton‡

It has seemed to me that in the guidance of chemical work by ore-carrying solutions there are really two kinds of control: First, a frankly mechanical control in which the solutions move by flow under hydraulic pressure. In that case the mechanism of transport of the chemical components, whether valuable or not, whether incoming or displaced and outgoing, is accomplished by bodily circulation of the medium, and for such circulation obviously some kind of open space is necessary. Material as solid as a perfect crystal, or material as solid as many aggregations of crystals may be, has openings, if at all, so small that the frictional resistance to flow of a fluid is enormous; therefore, the rate of flow through such material presumably is negligible and wholly inadequate for an accomplishment of such magnitude as the production of an important ore body. That kind of movement, if the channelways are adequate, is, of course, very effective. It is high-speed movement; express service, if you will. And its consequences are obvious; I suppose the vein, a deposit formed along a localized tabular channelway, is the commonest type of ore deposit we have.

There is another and quite different mechanism of transport which often we cannot ignore. Solid crystals are replaced, aggregates of crystals that seem to be essentially as tight as cast metals, are replaced by new material. The process sometimes utilizes a portion of the atoms already present, as when limestone is replaced by garnet or quartz; or the new elements may displace all that were originally present, as when limestone is replaced by pyrite. Such replacement processes do go on in relatively dense rocks and in some places on a very important scale.

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† Mining Engineer and Geologist, San Francisco, California.

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Are we going to assume that in such cases by some means the frictional resistance to flow along minute openings is magically reduced; or, on the other hand, are we going to assume that the process took so long a time that even with the almost infinitesimal rate of flow there was opportunity for the accomplishment of a great job of chemical transference of new materials in and of old materials out; or, finally, are we to look for some other mechanism?

As some of you know, I am persuaded that there is a second mechanism of importance besides the mechanism of flow. This, of course, is not novel at all, but I should like to see it emphasized more—the diffusional mechanism of transport, in which the ions move selectively, not by hydraulic head, but by what we might call physicochemical head; namely, differences in concentration from place to place.

The metallurgists in particular, in their exceedingly skillful applications of physics, chemistry and microscopy to the study of crystals, have become so familiar with the diffusional migration of chemical material within single crystals and through aggregates of crystals that they take it as a matter of every-day course. It seems to me that they have shown us the way for explaining many cases of replacement in dense material. Fractures are here merely the main trunk lines of wholesale transport; and branching away from the larger fractures are smaller ones, and still smaller ones, until at last fracturing and finite opening cease. Replacement is not thereby necessarily brought to an end; on beyond the limits, whatever they may be, of the finite fracturing, which permits circulation and flow, goes this selective chemical transport by diffusion. It has this advantage over the hydraulic: in the hydraulic channelways, in general, only one-way traffic is possible; all components of the solution must move in the same direction and at the same rate. The replacement job has two kinds of material to deal with, it has that which is brought in and that which is displaced. Diffusion has the advantage that it can handle two-way traffic—that is to say, the incoming, replacing material may move in one direction and the outgoing, displaced material may move in an opposite direction even in the same solution. This, it seems to me, does solve one big puzzle of replacement.

Naturally, I do not want to leave the impression that I minimize the importance of open channelways through which circulation is permitted. The relative rates of transport in terms of feet per year, let us say, when the widths or diameters of the channelway openings are substantial, are so greatly in favor of flow as contrasted with the much slower accomplishment of diffusion that when the channelway control has a real chance it utterly outstrips the other. It outstrips the other but never displaces it; diffusion goes on at the same time. When the finite channelways become so tiny that flow is practically zero, replacement is not brought to an end, as I see it, but continues to operate through the mechanism of diffusion.

This, I am sure, is not nearly as challenging as, for instance, Professor Bateman's proposal, but it is something that I should like to see elaborated eventually, if not now.

EDWARD SAMPSON*

Everyone that has even a moderate acquaintance with ore deposits is impressed with the importance of fractures in the formation of large masses of ore, but I think those who have seen thin sections of igneous rocks apart from ore will be impressed, as I have been, with how permeable a seemingly very tight rock may be, as, for instance, in the widespread sericitization of granite, or some of the alterations that take place in very dense volcanics. Although I do not offer an explanation, it does seem that observed facts call for the ability of solutions to penetrate rocks that seem to have little in the way of substantial opening.

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R. H. Clarke*

I think that the majority of mining engineers study structural conditions more than the chemical characteristics or mineralogy of an ore deposit. My experience would lead me to believe that deformation or fracturing is always necessary for the migration of mineralizing solutions in pure limestone.

L. C. Graton

Before we bring the discussion actually to a close, I wonder if Dr. Newhouse would say a word about some interesting data that he has assembled on the matter of structural controls, just to give this group forewarning that such a thing is in the offing.

W. H. Newhouse†

The Committee on Processes of Ore Deposition of the National Research Council has for the past two years been collecting a group of manuscripts from geologists intimately acquainted with the structural relations of the ore deposits of mines and ore-bearing districts. We have on hand about 75 such studies. I hope that we may be able to publish this collection during the year 1940.

George B. Langford‡

I cannot picture a dense rock such as limestone or shale, which is at all extensive, that would not have bedding, jointing, flow or fracture cleavage, folding, or faulting developed to a greater or lesser degree. If such a rock is deeply buried, but not to the extent of being recrystallized, such lines of weakness might be nearly obliterated, but I doubt whether they would be completely healed. Such lines always will be present to guide solutions, and should offer good channels for heated vapors under pressure.

On the other hand, geochemists tell us that ore-forming solutions coming from magmatic reservoirs are hot, acid vapors. Such corrosive gases, under pressure, should be able to make their way through any rock if given sufficient time, whether or not there was any pre-existing line of weakness to be followed.

Though I am of the opinion that magmatic vapors can migrate through limestone, etc., without any structural deformation, I doubt whether it is ever necessary for them to do more than find their own way between nonconnecting lines of structural weakness.

C. H. Behre, Jr.

"Always" is a strong word. Yet anyone asked to cite an important nonferrous metal-mining district in which deformation was clearly *not* present would be hard-pressed. Even a few of the cases which seem most free from local, fracture-producing tectonics prove, on closer examination, to be characterized by some type of deformation. Among these might be pointed out (1) the Witwatersrand, (2) the Sudbury type, with nickeliferous pyrrhotites, (3) sulphide-bearing contact-metamorphic deposits, and (4) the "flat-lying" lead-zinc ores of the Mississippi valley type. In all these cases careful examination proves the presence of ore-bearing fractures or other evidences of "ground preparation" by tectonic forces.

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The Witwatersrand has already been briefly but critically discussed by Dr. D. H. McLaughlin, who pointed to the existence of en echelon fractures. Of still greater significance are Dr. McLaughlin's remarks on bedding-plane fractures, some of which bear gold. The importance of such bedding-plane cracks and faults[4] is, I believe, largely underestimated, especially so for two reasons: (1) undoubtedly they occur in most competent sedimentary rocks or lavas that have been deformed; (2) they have the effect of distributing the ore widely horizontally and hence are frequently ignored in view of our search for vertical, more conventionally "hypogene" channels.

To discuss deposits of the Sudbury type is to "rush in where angels fear to tread." The theory of magmatic segregation in situ, developed by Coleman[5] and others, is very tempting; but there is no denying that, in later years especially, a large part of the ore is yielded by the "offset" type of deposits, to which Coleman's theory is not applicable. No doubt the general association of deposits of this type with basic sills is of genetic significance in respect to the ultimate source of these mineralogically aberrant solutions and the accompanying sills. But the mode of occurrence is equally certainly of real structural significance. By this I wish to emphasize that the intrusion of the sill commonly is followed by collapse, yielding the familiar lopolith,[6] which acts as an efficient blanketing body after the subsidence of the lopolith has produced fractures that serve as channels for rising solutions. These fractures are probably in part localized, like those near bedding planes, by differential movements along the contact between the sill and the underlying beds; they are represented by the "offset" bodies at Sudbury.

As to contact-metamorphic deposits, a large part of their metalliferous minerals is clearly later than the development of most of the typical "halo" minerals. This is strongly shown in many copper deposits, where the copper ore minerals themselves may be said to be classed as pyrometasomatic by courtesy only, because they occur in silicate zones near the contact. The sequence (1) silicates and other typically pyrometasomatic minerals and (2) ore minerals can even be applied to iron oxide deposits hitherto classed as pyrometasomatic, as has recently been shown for at least three carefully studied localities.[7-9] If generalizations are justifiable, these facts suggest that the contact-metamorphic ore deposits owe the localization of their *ore* minerals to: (1) porosity resulting from recrystallization in the halo, and, in a larger sense, (2) the complex zone of channels resulting from cavities and shattering near the contact between the intruded and intruding rocks. This channel zone probably leads to greater depths than penetration by ordinary fractures and thus affords access from the deep sources from which the ore solutions are generally believed to be derived.

As to the so-called "flat-lying" lead-zinc ores of the Mississippi Valley, all authors who have recently made careful studies of these deposits agree that the ore is either in or associated with joints (as in southeastern Missouri[10]) or in and near small planes of movement (as in the Tri-State district[11]) or in bedding planes opened by tectonic movements.[12] In Europe deposits that are mineralogically closely similar and structurally not greatly unlike are extensively faulted and fractured; examples are Mesiza in Yugoslavia, Bleiberg in Austria, Cave di Predil in Italy, the deposits of Vieille Montagne in Belgium and of Aachen in Germany, and those of the Mill Close mine in Derbyshire, shortly to be described in great detail by Traill.[13]

On a preceding page Dr. Graton suggests by implication the help that chemists and physicists may give us in the problems of replacement; he calls attention to the replacement of "tight" aggregates of crystals. In this connection two points have been especially interesting to me—one a fact, the other a possibly legitimate deduction. The fact is that much apparently "tight" rock is fairly readily subject to penetration "en masse" by solutions that did not follow any obvious shatter planes. The occasional limonite stains observed *in the interiors* of such rocks as granites and and limestones are typical. Several investigators of the process of dolomitization have used diffusion as a means for internally staining limestone that contained no visible fractures. Dense agate and quartz may be artificially stained by diffusion, as is well demonstrated in many beautiful museum exhibits. These are facts illustrating that ordinary solutions, and presumably mineralizing ones as well, may penetrate apparently dense rock, even where shattering is not observed.

As to replacement, I wish to suggest a possibility. Suppose a "blind" crack leads to the interior of a limestone, admitting a mineralizing solution bearing, say, many ions including lead, chlorine and sulphur ions. Ionic diffusion rate or "fugacity" is determined by factors among which are the weights of the ions concerned; hence chlorine ions diffuse more rapidly than those of lead. If a solution contains numerous positive and negative charges, ions of a certain element may exchange positions with those of another and still maintain the various parts of the solution in balance; chlorine ions, having a higher fugacity than those of lead, could move to and attack the borders of the crack, aiding in the removal of the calcite, now altered to soluble $CaCl_2$ and to CO_3 ions. Thus minute cavities would be developed along the feeding fissure, each cavity now filled with the solution, locally lean in Cl ions, the chief agent for keeping PbS in solution; PbS would therefore be free to deposit. Ca ions moving backward, as inferred from the gas laws, to regions of lesser calcium concentration, the chlorine-rich border of the liquid in the cavity might continue its solvent action. Meanwhile PbS, insoluble in neutral solutions, would be favorably situated for filling the space just left and might conceivably precipitate out in the form of PbS. As long as the solid PbS did not become so dense that it served as a tight barrier preventing the migration of the Ca ions back into the liquid, this process might continue. Theoretically three zones would thus be recognizable; from the edge of the host rock toward the center of the vein, these would be: (1) a microscopic film of $CaCl_2$ in solution, in which the Ca ions would be largely traveling toward the vein, to equalize Ca ion concentration throughout; (2) a narrow film lean in Cl ions at any given moment and therefore tending to precipitate PbS; and (3) the vein proper, filled with solution in which Pb, S, and Cl ions would be moving outward toward the newly opened areas while Ca (and CO_3) ions would be moving inward, having been added to the solution by reaction of the latter with the wall rock. Thus the smallest tectonic crack or cleavage opening sets up a mechanism favoring continuous change as long as participating ions are available, whether the system be closed or open, or under a head or not.

S. F. KELLY*

Rock density, in the sense of compaction or relative porosity, is discussed in Lawrence B. Wright's comments. From a geophysical angle it is possible to shed further light on this question of rock porosity, and hence permeability to migrating solutions. The angle of approach is that of the geophysicist using electrical methods. We know that the rock-forming minerals themselves are silicates, and therefore are practically nonconductors of an electric current. Yet I know of no place where any geophysical work has been carried out where it has not been possible to pass a substantial electric current through the ground. The only way that such a current can traverse soil or solid rock is by virtue of the electrolytic conductivity of the moisture absorbed in the pores of such formations. Such moisture inevitably carries in solution certain salts derived from the minerals with which it is in contact. The dissociation of these salts renders the moisture electrolytically conductive. Because of the essential continuity of such electrolytically conductive moisture throughout the rock mass, the latter is endowed with electrical conductivity. From geophysical experience I think we are warranted in saying that, as far as we know, all rock formations, even the densest, are sufficiently porous to contain appreciable quantities of electrically conductive moisture. The formations that come nearest to being exceptions are massive quartz veins and solid rock salt.

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Question 2.—What Are Some of the Chemical and Physical Characteristics in Certain Beds within a Limestone Formation that Determine Their Favorable or Unfavorable Aspects as Reservoirs for Ore and Other Introduced Minerals?

DISCUSSIONS

JOHN S. BROWN*

Intimate acquaintance with a number of lead and zinc deposits in metamorphosed limestones seems to indicate the existence of certain common features from which can be established some general principles governing the localization of ore in this type of formation. It is suspected that these principles can be applied, with modifications, to mineralization in unmetamorphosed limestone. In metamorphosed formations, some observed rules are as follows:

1. Bands or masses of pure limestone are very resistant to replacement by ore solutions, and are likely either to contain no ore or to resist replacement until near the end of mineralization. The reason for this apparently is physical, not chemical, since microscopic data indicate that when ore is deposited by far the greater part of it substitutes for carbonate. The chief factor is believed to be a lack of porosity in massive limestone that has undergone flowage and recrystallization.
2. Masses of intensely siliceous or silicated rock are likewise unfavorable ore receptacles. This seems to be accounted for by two factors; (*a*) chemical unsuitability or resistance to replacement, and (*b*) physical resistance to small-scale brecciation and opening of effective channelways for solutions. Some low-grade ore may occur, however, and also sporadic fracture fillings.
3. The optimum condition for ore reception appears to be found in bands or masses containing carbonate and silicates (or quartz) intimately mingled in something like equal proportions. In this situation movement is likely to result in mixed flowage and fracture, producing a fine-textured porosity that admits solutions freely and provides access to an abundance of replaceable carbonate. Cleavage cracks in some minerals such as diopside are believed to facilitate the penetration of solutions.
4. Certain minerals or assemblages are regarded as favorable impurities in a limestone and others as unfavorable. Original quartz, and subsequently developed diopside, and perhaps garnet, are typical favorable premineral gangue matter—in general, rather equidimensional, brittle minerals. Tremolite, biotite, and probably wollastonite, are typical unfavorable premineral gangue—in general, highly elongated and somewhat flexible minerals likely to develop under strong shearing stresses.
5. Tentative opinion is that the ratio of lime and magnesia in a limestone is of little or no importance.

It is proposed to illustrate the foregoing principles by data from two typical deposits, the Aguilar lead-zinc mine in Argentina, and the Balmat zinc-pyrite mine in New York.†

As applied to unmetamorphosed limestone the suggestion is that permeability is the chief factor. It may be supplied by bedding planes, brecciation from any cause, dolomitization in some cases, and doubtless by other means. Combinations such as bedding and brecciation are especially important. Lack of effectively dispersed channelways probably makes bedded limestones inhospitable to ore at many places.

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† See pages 250 et seq., this volume.

G. W. Bain*

May I have just a few minutes to take up this subject, particularly the widths of openings in rock and their effects on mineralization.

The question of the influence of the physical characteristics of a rock upon mineralization within it has interested me for a considerable period. For a number of years I have been working on the problem of width of openings in a rock and what happens to solutions when they are in these openings, particularly the extremely narrow ones.[15] The reason that any solvent is able to carry solid substances is that the solution is capable of either taking up more material or giving up some of the substances it contains in response to slight energy changes in it.

One cause of change in the energy of a solution is adsorption of some dissolved solids on a surface and the amount of adsorption that can take place is a direct function of the area of the adsorbing surface. The area of adsorbing surface in a rock has been found experimentally to be a function of the number of grains in a rock and can be estimated as follows: the length of contact between the grains exposed on any surface of crystalline rock divided by the square root of the number of grains in that crystalline rock is equal to (2 ± 0.2). That is measured in a section.

Let L = length of contact between grains in each square centimeter,
G = number of grains exposed per square centimeter,

Then $$\frac{L}{\sqrt{G}} = 2 \pm 0.2 \qquad \text{or} \qquad L = (2 \pm 0.2)\sqrt{G}$$

Let A = length of side of a cube of crystalline rock,
Then L is a function of A^2, or $L = f(A^2)$
And $$L^{3/2} = f(A^3)$$

Therefore the area of contact of grains per cubic centimeter is $L^{3/2}$. Simply, the length of contact between grains in any area can be converted to the area of contact in a solid of the same material by raising the length of contact to the three-halves power.

The width of openings in a rock is another significant physical property that is important and determinable for crystalline rocks. It is calculated from the area of grain contact and the total pore space; pore space is the product of the area of contact between the grains and the width of opening. The pore space can be measured and the length of contact can be measured or estimated from the equation:

Let $L = (2 \pm 0.2)\sqrt{G}$
V = volume of pore space,
w = width of opening,
then $$V = wL^{3/2}$$
$$w = \frac{V}{L^{3/2}}$$

The value for V varies somewhat in crystalline rocks but rarely falls below 0.3 per cent or exceeds 1.0 per cent. However, the grain size varies widely and so the value of L fluctuates through a range that may cause a thousandfold variation in w. In many rocks the width of opening becomes extremely narrow, so that solution is spread over a large area and the change in energy is so great that certain substances are dropped from the solution to form a surface film over each of the individual grains in the solid. If the openings are wide, a very small quantity of solute is left and the change proceeds with extreme slowness. If the openings become too narrow, ingress of solutions may be inhibited even though conditions for adsorption may be at an optimum.

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Pure limestone usually reorganizes under metamorphic influences into very large crystals; openings in such a rock are wide and the area presented for adsorption from solution is usually low, so that rate of replacement is at a minimum. Impure limestones are usually finer grained; their openings are so narrow that the solutions are unable to bring in enough material to be adsorbed on the grain surface and metasomatism is extremely slight. Some intermediate condition gives best results. I have seen these influences in a number of deposits on a minor scale. Study of the relation of adsorptive energies on these rocks and the width of openings or indirectly the area for adsorption yields an explanation for many phenomena associated with metasomatism. Structures influencing grain size and width of openings are probably responsible for the many metasomatic deposits in crystalline rocks and in incongruous positions in them.

L. C. GRATON

On behalf of Professor Bain and myself, I apologize for the introduction of some highly academic questions into something that is really practical. I am going to call upon some representative of the Geological Survey to give perhaps some other point of view. Is Dr. Loughlin here?

G. F. LOUGHLIN*

I have nothing to add to what has already been said, but I can cite a few additional examples to confirm an opening remark of the discussion.

During the World War we were asked to recommend stone suitable for use in building acid towers and it was necessary to fall back on natural stone, as chemical brick were not desirable, for some reason. We tested a number of granites. One granite in particular, from Rockport, Mass., was especially interesting because, although it had resisted weathering excellently when used in buildings, it crumbled rapidly when subjected to 50 per cent nitric acid. The reason was that the black mica in that granite was an iron-rich mica. The rapid oxidation of the mica when touched by the acid, which penetrated minute cracks along fracture surfaces of the stone, caused it to swell and pry the minerals of the granite apart. As soon as the bottoms of those superficial cracks had been reached, the disintegration stopped.

To see what prolonged contact with the acid would do we had a bowl, about 6 or 8 in. deep and 4 or 5 in. in diameter, made in a single block of the granite, filled the bowl with acid and left it for 18 months. Then we cracked the block in two, polished the surface, and found that the acid had penetrated to a depth of about 3 cm. In the first centimeter it had extracted all the iron and coloring matter in the rock, and in the next two it had deposited it as a brown oxide. There were no cracks noticeable, but the discoloration in the brown-stained zone was almost wholly along mineral boundaries. Cleavage cracks had not been penetrated by the acid to any appreciable extent. In one place on the outside of the block there was a brown stain that I supposed had resulted from the spilling of a drop or two of acid, but when we cracked the block open we found that there was a blind seam too thin to be seen before treatment, but permeable to acid, which traveled from the bowl to the outside of the block. Elsewhere the granite between the border of the bowl and the outer surface was not stained at all.

That process illustrates, I think, the ability of solutions to penetrate unfractured rock and also shows that, in that particular granite, at least, the grain boundaries were more permeable than the cleavage cracks to that particular acid solution.

An analogous example might be cited from the oxidized zinc ores from Leadville, where manganosiderite had been replaced by smithsonite. Where the replacement was not complete the center of grains of the original manganosiderite were left intact, although many of them had been leached out during subsequent alteration, leaving a very fine network of zinc carbonate. Some of the ore examined was sufficiently coarse-grained for the process of permeation and replacement to be very clearly demonstrated. The replacing solution, no doubt, found its way into the rock along cracks and bedding planes, but, under such pressure as existed, it was able to penetrate through the largest masses of manganosiderite which previously had replaced large masses of dolomite. Microscopic examination of the manganosiderite showed that it also had been introduced by permeation along grain boundaries. It took major and minor fracturing to admit the solutions, first the manganosiderite solution from below, and later the zinc carbonate solution from above, but they both did their work in the same way.

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E. L. Bruce*

I rather wonder that nobody has suggested the other possibility—the possibility that some of the ore may be carried in some other way than in the liquid phase. I am sure if Dr. C. N. Fenner were here he would suggest that in some places at least the material might be carried in a gas phase. In some of the ancient volcanics bordering certain gold veins in Canada, we find a considerable amount of disseminated pyrite, and yet the total amount of iron in the rock remains the same; in other words, the pyrite could have been formed by reaction between H_2S and the iron present in the chlorite. That is a possibility that can at least be taken into consideration in considering the form in which ore travels from place to place. Actually, so little is known about the media or phases in which ore constituents are transported that there seems little upon which to base any conclusions as to the minimum size of openings through which the material may pass in its migration.

Reno H. Sales

The most important physical characteristic of a limestone bed is permeability. This has been pointed out by Mr. Brown and further stressed in my discussion of Question No. 1. An ore body may result from the filling of fractures, pore space, or other openings, or by replacement of the rock mass by valuable minerals. Of the possibilities just mentioned, replacement of the rock by ore minerals is extremely important, and it is in deposits of this type that the chemical characteristics of the host play such a vital part.

The expression "favorable bed" is sometimes heard in connection with ore deposits. It has reference, in fact, to selective replacement, but the roles played in the process by factors of permeability and chemical composition of the host rock, respectively, seldom form the bases of serious investigation.

In general it is possible in the field to recognize the favorable bed where ore replacements have taken place in a limestone series. But, in my opinion, there are few geologists, if any, that will attempt to name definitely the chemical characteristics that make one host rock more favorable to replacement than another. Impure shaly limestones, carbonaceous beds, dolomitized lime beds, and beds rich in animal or vegetable remains are commonly spoken of as being favorable to ore formation.

The chemical composition of the mineralizing solutions, temperature and pressure relations, and other factors, undoubtedly play important roles. Because of this fact, favorable beds in one district may be resistant toward replacement in another. For example, in Park City, Utah, the Janney quartzite is a favorable bed and highly productive; but at Bingham, Utah, in contrast, certain lime strata are exceptionally favorable ore carriers with adjoining porous quartzite showing little or no replacement although intersected by the same fissure feeders.

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In the Sullivan mine, near Kimberly, B. C., selective replacement on a large scale in thinly bedded, crumpled and folded shales produces remarkably beautiful ore specimens showing alternating thin layers of galena, sphalerite and pyrrhotite. In Montana and Utah the Hasmark formation of the Lower Cambrian limestone series appears to be particularly susceptible to replacement by sulphide ores. It is a thinly bedded rock and undoubtedly more permeable to solutions than the other more massive members of the series. I am not aware that any attempt has been made to learn what chemical characteristics make the Hasmark favorable for ore.

The question before us brings to attention an extremely important phase in the science of ore deposits, to which too little serious attention has been given in the past. It is to be hoped that Mr. Brown's analysis, together with the discussions that follow, will direct the attention and interest of students and investigators toward this promising field of research.

R. H. Clarke

I have seen occurrences of sphalerite and galena in limestone similar to those mentioned by Mr. Sales, in the Pend Orielle or Metaline district of northeastern Washington. Here the sphalerite and siliceous gangue comprise the main masses of ore, but the galena occurs as an outside lining, or in streaks and bunches, generally near the hanging wall. On this account the zinc concentrates from the district, recovered by selective flotation, are so free of galena that they command a better price than ordinary concentrates from other districts.

In the Silver Star district, Madison County, Montana, there is an unusual gold deposit in limestone parallel in strike and dip to its contact with the Butte granite. The ore, chiefly jasper, occurs in lenses along fractures at 15 to 30 ft. from the granite. The near-by minerals and those accompanying the ore are limonite, siderite and magnetite, as well as garnet, epidote, pyroxene, calcite—characteristic alteration products of a granite-limestone contact. The fissuring here may have been due to the shrinkage of the cooling granite or to the folding of the limestone beds at this particular locality.

A. K. Snelgrove*

Apropos of the subject of favorable wall rock and the suggestion that some of these questions might be investigated experimentally, I should like to propose that the problem of mineralization in pillow lavas might well come up for some scrutiny.

Perhaps I am somewhat influenced by my experience in Newfoundland, where pyritic copper mineralization in pillow lavas is rather widespread. The chloritization of these mineralized pillow lavas and associated dioritic intrusives is commonly intense, yielding a green schist known to prospectors as "killas" and rightly regarded as a favorable country rock for ore. On deformation the pillow lavas conceivably behave somewhat like a coarse conglomerate and the spaces opened up between ellipsoids provide a channelway for mineralizing solutions which replace the matrix and also the sheared pillows. Whether the ease of replacement of chlorite schist by mineralizing solutions or the peculiar physical setup is the dominant factor in the formation of such pyritic copper deposits merits investigation.

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George M. Fowler

In the Tri-State mining district the visual physical distinction between the strata that contain the predominant ore bodies and those that are barren seems to be:

Favorable—Thin-bedded strata with numerous stylolite partings.

Barren—Massive thick-bedded strata.

About 16 distinct beds are recognizable throughout the mining district and they are nearly equally divided between the favorable and barren variety. All the beds are barren except in disturbed zones.

Structural deformation is very intense in parts of the district. It created the zones of adjustment, which became, in many places, the reservoirs for the ore-bearing solutions. These zones or reservoirs are of three general types: (1) shear zones of many sizes and shapes that cut the strata at nearly vertical angles; (2) openings along the bedding planes and stylolite partings; with or without shattered strata between them; (3) combinations of these two types.

The optimum conditions for major ore reservoirs are wide, strong, and intensely shattered shear zones, which gradually merge into deformed and fractured strata.

C. H. Behre, Jr.

For some time the writer has been interested in this question. The studies of Hewett at Goodsprings, Nev., point to a close connection between dolomitization and mineralization, at least mineralization of the lead-zinc type.[16] This connection, observed in so many other places as well,[17] might suggest that the association of dolomite and ore, in some instances, at least, is due to an identical source for the ore-bearing and the dolomitizing solutions (it being clear that in some places at least the dolomite is secondary and represents an early phase of the mineralization). Or the association between ore and dolomite might be purely fortuitous, Paleozoic dolomites being widespread anyway, and hence *necessarily* frequently the host rock of any ore occurring in Paleozoic areas. Or again, the association of ore and dolomite might indicate that dolomite is a preferred host rock for physical or for chemical reasons. What follows seems to the writer to be evidence in favor of the last viewpoint.

There is no intent, however, to oppose the contention that the reason for the association of dolomite and ore in many districts is that both represent hypogene mineralization from essentially the same source. The absence of calcium-magnesium carbonate and the presence of siderite in deposits exhibiting the same ore minerals but occurring in schists and slates instead of in limestones seems to suggest that the dolomite was not a primary constituent of the mineralizing solutions; examples are the sideritic veins of the Coeur d'Alene district, those of the north British ores in the Lake district slates, and those of the schist province in the Rhine region.

Of the larger European districts bearing lead-zinc ores of the "Mississippi Valley" type, it can be confidently said that the ore generally occurs in dolomitic rocks, as opposed to pure limestones; the only conspicuous exception of which the writer is aware is Bleiberg. A yet more correct statement, and one that applies virtually to all of the lead-zinc mines in Europe, French North Africa, and the United States, is that wherever the stratigraphic sequence includes *both* limestone and dolomite, the ore seeks out the dolomitic layers preferentially or occurs in parts of the beds that have been dolomitized. Among Mexican districts showing the same feature, Hayward and Triplett cite seven (including Santa Eulalia) in Coahuila, Nuevo Leon, Durango, and Chihuahua.[18]

In the neighborhood of Allentown and Bethlehem, eastern Pennsylvania, the upper Cambrian and lower Ordovician is made up largely of alternating beds of limestones and dolomites. Field observations, confirmable in published photographs, show clearly that the dolomites break in closely spaced, clean joints, while the limestones fracture irregularly. Analyses and illustrations are given by Miller.[19] An excellent exposure of the Allentown limestone shows close jointing in light gray to buff dolomites and absence of jointing in slaty gray limestones; this may be seen in the Central of New Jersey Railroad cut along the Lehigh River in north Bethlehem. This difference probably is due to the capacity of the limestone to recrystallize instead of fracturing under stress. Much the same conclusion, with some variations, was reached by Hewett[16] in regard to mineralization at Goodsprings, Nevada. Hayward and Triplett also reached this conclusion.[18] The Committee on Processes of Ore Deposition of the National Research Council several years ago suggested the investigation of this tendency to fracture in dolomites, as compared with limestones; unfortunately, no such studies have been completed in so far as the writer is aware, but qualitative observations like those cited seem to confirm the conclusion given above. Moreover, the further inference seems warranted that this is the chief reason why ores are commonly found in the dolomitic areas, whether the dolomite itself is a primary sedimentary or diagenetic feature or is formed much later as a hydrothermal alteration product of the limestone.

It must be admitted that there are other modifying features, even after due allowance is made for dolomitization. In Silesia the zinc ores occur in dolomitic measures, but chiefly in the lower part, where the dolomite beds, when unreplaced by ore, are massive. A few mines in the outlying parts of the Leadville district, Colorado, show mineralization in the higher parts only of the Leadville dolomitic limestone; analyses of carefully selected, representative samples extending from top to bottom of the formation show no chemical differences adequate to account for the localization of the ore. In the Continental Chief mine the ore is apparently localized to massive beds that break in long, continuous fractures or joints, as opposed to the barren beds, which, chemically similar, customarily shatter in irregular fractures, running only between beds and hence (the beds being thin) generally short.*

In summary, therefore, I believe that one very important factor in the localization of ore beds in limestone is the manner of fracturing of the dolomitic beds, conditioned by their resistance to recrystallization. Within two chemically identical dolomitic beds, the thicker is the more favorable because its fractures are more nearly rectilinear and, yet more, because massive beds have less tendency to flow.

Question 3.—Are There Any Criteria by Which One Can Determine When Mining Operations Have Reached the Roots of an Ore Deposit?

DISCUSSIONS

GEORGE M. FOWLER

The writer should have stated this question more clearly; a better question would have been: Are there any criteria by which one can determine when mining operations have reached the deepest limits of the ore?

IRA B. JORALEMON

Before discussing the criteria as to when the roots of ore bodies have been reached, it is necessary to decide just what is meant by "roots." Two interpretations of the term are possible. The first is the bottom of the workable ore—including perhaps the channel through which solutions came. This is usually the bottom of the local area in which ore deposition took place, and so is purely structural. Often ore comes in again deeper down along the same channel. The conditions determining the "root" as so defined differ with every ore body. No generalizations, and so no significant discussion, can result if this definition is accepted.

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* Statements about Leadville made with the permission of the Director, U. S. Geological Survey.

The second definition, which is probably the one contemplated in the question, considers the root of any ore body to be the place from which the ore came, and so the horizon below or beyond which no further ore can be expected. This sort of root may be separated from the ore body itself by many thousands of feet in which structure prevented ore deposition—and there may be several ore bodies separated by lean or barren areas, yet emanating from the same root.

Using this second definition, the question becomes of considerable theoretical interest. As far as my experience goes, the interest is seldom more than theoretical. For I can recall hardly an instance where mining development has reached the real root of the mineralization.

In Bisbee, for instance, typical ore occurs where certain limestone beds are shattered by fracture zones. Under the ore, the fracture zones in the deeper limestone beds usually contain only a little limonite, which clearly was brought in by surface waters. These certainly are not the roots of the ore. If one follows the intersection of fracture zones with favorable limestone beds toward the center of mineralization—the Sacramento Hill porphyry stock—one passes through alternate ore bodies and lean or barren areas until one reaches the broad band of silicated contact breccia that surrounds the porphyry. This breccia ring might be considered the locus of roots. But intense mineralization with pyrite and some copper ore continue down in the contact zone to the greatest depth yet reached. If the root is considered to turn down steeply in the contact zone, it need not mean the end of ore, as other ore zones may branch off in deeper limestone beds. Even in the schist, more than a thousand feet below the ore-bearing limestone, drill holes in the Irish Mag claim found material assaying 2.5 per cent copper and further development might find at still greater depth ore that came from the same source as the limestone ore. The roots of Bisbee mineralization have been found only in the sense that the bottoms of structures that localized certain ore bodies have been reached. The true root that would be the bottom of possible copper ore may be many thousand feet deeper.

The Ajo district is perhaps the best example of a "disseminated" copper ore body, as there is little complication owing to supergene enrichment. In the Ajo ore body narrow bands of deep ore spread out from their respective channelways and join as they approach the present surface near the horizon where a porphyry intrusion domed up overlying rhyolite and other earlier lavas. The reason for the great ore body was the widespread shattering of the porphyry immediately under the relatively impervious rhyolite. Mineralization of the same type as that in the "disseminated" ore has been found along larger fractures many hundred feet below the bottom of the big ore body, and further mining development may prove that it extends thousands of feet deeper. The roots of the Ajo mineralization have not been found, but only the bottom of the widespread ore body.

It is conceivable that if there had been a few great fissures instead of shattered rock under an impervious capping, Ajo might have been a vein district like Butte.

While I am not familiar with recent developments in Butte, it is my understanding that in some veins the workable copper mineralization has given place in depth to lean quartz and pyrite. In other veins high-grade copper ore recurs at still greater depths below the lean quartz and pyrite. The true roots of the Butte veins have not been reached. The bottom of ore deposited by one wave of mineralization may be determinable, but the source of ore is so much deeper that several other ore bodies may be found at lower horizons in or along the same fissures deposited by other mineralizing waves.

Breccia chimneys of copper ore in several instances have been developed down to structural roots, where the breccia gives place to more or less open fissures filled with lean quartz and pyrite. Even these are probably not true roots. The brecciation, in many places at least, seems to have occurred long before the mineralization started. Then the solutions, rising from much greater depth, chose the chimneys as a convenient place in which to deposit their mineral content. It is entirely possible that veins of copper ore may be found along the feeding fissures far below the bottoms of the chimneys. We know nothing about the real roots of the mineralization.

Lead-zinc veins sometimes change in depth to lean pyrite material or to copper ore. The points of change can hardly be called the beginnings of true roots, as the source of mineralization probably is far away. Other ore bodies, of the same or other metals, may occur between the bottom of the known lead-zinc ore and the true root.

The gold-quartz veins of the Mother Lode area in California are excellent examples of the difficulty of recognizing the roots of ore. Many rich mines have passed down into lean pyrite plus quartz, owing to which the mines have been abandoned. But other mines have gone below similar lean vein material and developed recurring bodies of commercial ore to a depth of many thousand feet. As far as I know there is no indication that the end of gold mineralization has been approached. The question is not whether new ore bodies may be expected in depth, but whether they are worth hunting for. Mines are abandoned because they have come to the roots of the bank account, not of the ore.

In the shallower bonanza-type gold and silver ore bodies of Nevada and neighboring states the situation is not so clear. The volcanic rocks in which the veins occur change and in some places peter out entirely at relatively shallow depth. It is difficult to say whether most of the mines in this area are comparatively shallow because of changes in structure that governed deposition of ore or because their real roots are shallow.

Examples could be multiplied indefinitely. Now and then a mine ends in depth with a change in mineralization that may possibly mean that development is at the roots of the ore. This is seldom if ever proved. Far more often there is simply a structural change, and not the real bottom of mineralization.

From a practical point of view the possibility that structural change may soon end the ore body in a mine or prospect is the most vital problem. The chance of finding other ore bodies that come from the same source is nearly as important. In most cases neither of these problems has anything to do with the real bottom of the mineralization. If structural conditions are favorable, it is safe to assume that the roots of the ore are so far away that they have little bearing on the worth of the mine.

Reno H. Sales

I doubt that the expression "roots of an ore deposit" is much used in our mining fraternity or among geologists. Mr. Joralemon has pointed out clearly the difficulties we face in attempting to apply it to ore deposits in general. I believe the term "root" to be applicable to ore deposits in a very restricted sense. It is neither scientific nor satisfactory.

In ordinary usage the root of an ore body means the deeper and noncommercial part of the deposit. In a fissure-vein ore shoot, for example, the lower limit of the ore, or the zone of transition from ore to the barren portion or root, may depend upon the market price of the product, cost of mining, and other factors. Geologically, the ore may pinch to unworkable dimensions, or it may split into stringers, or become deficient in valuable metal. One or all of these conditions may be present. These unprofitable downward geological extensions are sometimes called the roots of the ore body. This may be the geological picture the author of the question for discussion had in mind.

Acceptable criteria for one district may have little or no application in another. Western United States and parts of the Appalachians are dotted with "worked out" mining districts. Unquestionably in many of them the mine workings, or deeper level tunnels, demonstrated the ore bodies to be of limited vertical extent, although the containing fissures, or shall I say roots of the deposit, were disclosed as continuing to unknown depths. As the mines were deepened during early mining stages, those in active charge saw changes in physical character and mineralogical composition. Some of the changes in fact meant the beginning of the end of commercial ore. These criteria, probably recognized and made use of in some instances but never recorded for posterity, were proved later by deep development to be dependable, but useful only in the district in which the observations were made.

Experience in Butte, Grass Valley, Bingham, the Mother Lode district, and many other camps, has proved the futility of trying to apply criteria broadly, notwithstanding that certain factors appear applicable to individual ore shoots. At Butte, mineralizing processes have been too complex to permit the application of simple formulas. At Bingham and Bisbee, as well as at Butte, ore shoots bottom or pinch out, but often they are succeeded in depth by others of equal or greater value. In these districts, and in other areas still productive at greater depths, it will be in the final deep level development phases only that the operator will find it possible to establish reliable positive criteria in answer to the question here proposed.

G. F. LOUGHLIN

Referring to Mr. Joralemon's comments upon the roots of deposits, I can cite the Portland mine in the Cripple Creek district, where there is no root in sight yet, although the commercial root has been reached three times. First, at about the 1200-ft. level, the miners ran out of good ore, although the vein fissure containing fluorspar, quartz, and adularia persisted. Exploration continued downward for 300 ft. more and disclosed ore of a grade that justified mining. That ore was followed downward to the 2000 or 2100-ft. level, where mining was again suspended, though largely because of the World War, which had produced such unfavorable conditions for gold mining. Later, the company raised a few hundred thousand dollars and gambled on going deeper. They sank the shaft to the 2600-ft. level, crosscut to the vein, and got enough ore to encourage them. On the 2700-ft. level they ran into a good ore body that continued down to the 3000-ft. level and put the mine on a dividend-paying basis again. They went down to one more level, the 3100, but could not find a sizable body that was worth calling ore. They did, however, tap a flow of water sufficient to discourage further exploration. The 3100-ft. level was about 1000 ft. below the drainage-tunnel level.

When the structural conditions of the Portland mine are considered, with due regard to the pitch of ore body, there is no apparent reason why, if further exploration of the vein should be undertaken for two or three hundred feet along its strike and two or three hundred feet down its dip, another ore shoot could not be exposed but with this qualification; as somebody has compared fracture systems to an apple tree, the lowest workings of the Portland mine are down along and perhaps beyond the trunk of the tree. The deep fractures are tighter and very little evidence of vein deposition is found outside of the main fracture zone; so it is a question whether or not the character of the rock is such that the fracture has been open enough or has split sufficiently into minor fractures to permit an ore body of commercial size to form. The kind of rock throughout that mine has had a great deal to do with fracturing and therefore with the size and distribution of ore bodies. There is a chance that the rock below the present workings may be mainly syenite, which was relatively resistant to deformation, whereas the breccia, in or along which good ore bodies have been mined, was more easily fractured. If so, even though the ore zone may continue the hope of finding an ore body of commercial grade may not be very encouraging.

The Cresson mine, in the same district, also has gone well below the drainage level. Its ore was associated with a pipe of basaltic breccia, or a "blowout," as they call it. That "blowout" had the shape of a bicuspid tooth. Near the 1800-ft. level, it divides into two roots: one root tapers downward so markedly within the next 200 or 300 ft. that apparently it comes to a point a few hundred feet farther down; the other has hardly tapered at all. The ore bodies have been within, but mainly at certain favorable places along the margin of the "blowout," especially where it is joined by fracture systems that cut the surrounding rock. Those fracture systems have been productive down to the deepest level of mining and still further deepening would be justifiable if the cost of mining permits.

If it were feasible to drain the district well below the present drainage level, the grade of ore in sight and the present price of gold should encourage still deeper exploration and should approach nearer to the real roots of that ore body, which presumably are down in or below the roots of the complex Cripple Creek volcano.*

FRANCIS A. THOMSON†

I am glad Mr. Joralemon has emphasized that the bottoming of one shoot of ore is not a reason for assuming that another shoot cannot occur below. Ore shoots in the same vein are separated from each other horizontally by virtually barren or low-grade vein material as a matter of course, and there is no reason to suppose that the same thing cannot happen in the vertical plane; in fact, we know that it does, aside entirely from changes in mineralization. Naturally, from economic necessity mining operations normally would cease long before the actual roots are reached, consequently we must look elsewhere for vein roots, and the logical place to find them is in areas where they have been exposed by erosion.

For example, some 15 years ago, while engaged in a study of the gold areas of north central Idaho, my attention was attracted particularly to the utter inadequacy of the existing veins as a source of the recorded placer production. The miner's usual assumption that placers of consequence imply a great "mother lode," from which the placer gold has been derived, had its origin in the California gold fields and seldom has been duplicated elsewhere. Thus, we find in many of the formerly productive placer areas no such lode gold deposits as those from which the placers must obviously have been derived. The remnants of gold veins remaining after the erosion that has been responsible for the placers must represent in considerable measure the roots of veins that must have been much larger and probably much richer than the present remnants would indicate. The old placer camp of Florence, Idaho, produced conservatively about twenty-two and one-half million dollars out of a total of fifty-seven million credited to all the north central Idaho placer areas, but as I wrote at the time:[20] "Erosion has been so extensive in this region that there is but little left of the original quartz veins (however) numerous occurrences of narrow zones of countless small parallel auriferous quartz stringers are to be seen."

Any reasonable allowance for the amount of erosion that has taken place in this drainage basin, coupled with an estimate of the gold content per unit of volume based upon the surface now exposed, would fall far short of the undoubted placer production of the area. This fact, coupled with the appearance of the existing veinlets, certainly suggests that these are the roots, or rather rootlets, of veins of substantial volume and richness that have been worn away by erosion. Indeed, one is almost forced to the conclusion that these veins have "horsetailed" in their course downward. A somewhat similar condition exists in the vicinity of several of the old Montana placer camps. If these are not the roots of veins, I wonder what else they can be.

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* The New Carlton drainage tunnel in the Cripple Creek district is in progress at present and its completion is expected within three years. According to the *Engineering and Mining Journal*, the portal of the tunnel is at an elevation of nearly 7000 ft., or 1000 ft. below the old Roosevelt tunnel, the portal of which is 8033 ft.—G.M.F., Oct., 1939.

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It may be objected that fissures that are strong and wide cannot peter out downward into a series of ramifying cracks because these would fail to afford sufficient channelways for the upward rising mineralizing "juices," but the series of ramifying cracks are in the batholith itself and their relation upward to larger veins makes the analogy to tree roots almost an exact one. These ramifying cracks in the top of the batholith would naturally serve as feeders or gatherers of the solutions that have mineralized the upper part of the vein with which they connected. If this be true, ramification downward may well be one of the criteria by which one can determine when mining operations have reached the roots of an ore deposit of the fissure type. In fact, I have in mind at the present moment a highly productive mine in which there is some evidence of the fissure fingering out downward and I am beginning to be apprehensive as to depth extension.

Mr. Joralemon, in passing, mentions another extremely important subject; namely, the relatively shallow depth at which many veins of the Tertiary gold-silver type become impoverished. It is not my observation that this impoverishment is necessarily related to changes in structure or country rock, however, and I suggest that this is a subject that should be on the agenda for next year's discussion.

E. Y. Dougherty*

If we are considering criteria by which the original source of the hypogene ore-depositing solutions can be recognized, the question is probably indeterminate in most or all instances. But if we define the "root" as the deepest limit of the ore, the problem is susceptible to solution in specific cases. (It is probable that the deepest limit of the ore is seldom, or never, the original source of the ore-depositing solutions.) It seems to me that the question is hardly susceptible to an answer by generalizations; that is, universally applicable rules probably do not exist. But there are examples of ore deposits that bottom with significant structural or mineralogical changes and these present the opportunity to establish criteria by which the miner may know, without complete undercutting of the deposit, that the deepest limit of the ore deposit has been reached.

There are many examples of ore deposits that bottom with a bottoming of the ore-localizing structure or because of downward change in wall rock. Downward termination, tightening or dissipation of ore fissures and dying out, weakening or change in configuration of sheared folds that localized ore-containing fissures, are examples of structural changes that may cause bottoming of ore. Downward change from favorable limestone to other rocks is a well-known cause of the bottoming of certain ore deposits.

Mineralogical changes accompanying downward termination of ore are described in reports on various districts. These changes include impoverishment in depth of lead or copper ore bodies by increase in zinc blende, pyrite, or pyrrhotite. The inference is that such changes are instances where physicochemical factors rather than purely structural changes are the major cause of bottoming of the ore. Yet thorough enough study and analysis may show in these cases, as in many others, that structural changes in the enclosing rocks, or in the ore itself, were important causes of mineralogical changes. In some instances, depth impoverishment of gold in gold-quartz ore bodies in the pre-Cambrian areas of Ontario and Quebec has been observed to occur where calcite increases at the expense of quartz or where pyrite decreases or increases or where silicification or carbonatization of wall rocks weaken or die out. These mineralogical changes are conditioned frequently by changes in the mineralogical or physical character of wall rocks or by variations in fissuring.

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Though commonly it is difficult or impossible to be certain that the bottoms of particular ore deposits are even approximately the deepest horizons at which the valuable hypogene metallization of the ore-containing zone can occur in sufficient concentration to make ore, there appear to be occurrences where this is strongly indicated or proved. An instance that comes to mind is the Cobalt, Ontario, silver district. In this district mining operations proved a general lowest horizon of what is undoubtedly deposition of hypogene native silver ore, and established practical criteria by which this horizon was indicated. Reasonable explanations that go a long way toward explaining the relatively shallow termination of rich native silver ore at Cobalt were made by W. G. Miller.[21] These explanations were based mainly on the close genetic connection of the silver ore with the Nipissing diabase sill and upon the localization of fracturing of pre-silver vein minerals. Characteristic downward termination of the native silver ore shoots within several hundred feet of the bottom of the Nipissing diabase has been explained logically, in many cases, by downward tightening, termination or dissipation of the vein fissures. But C. W. Knight remarks:[22] "In the case, however, of veins which persist to unknown depths into the Keewatin, but lose their silver contents at or near the Keewatin contact, the explanation of the loss of silver at the contact is more difficult. Generally speaking, it is only the stronger fractures, such as faults, which persist into the Keewatin. Vein No. 64 on the Nipissing, for example, occurs in a prominent fault. This vein was explored downward into the Keewatin for 800 feet, but no pay ore was found in the Keewatin although the calcite vein persisted." Physicochemical factors apparently must enter into fully satisfactory explanations of the bottoming of the Cobalt silver ore deposits, as in many other cases where a purely structural explanation fails to encompass all facts.

From descriptions of the main lode of Dolcoath and Carn Brea, Cornwall, England, it appears that the downward change from predominant copper ore mainly in the overlying slates to predominant tin ore in underlying granite is an example of bottoming of concentrated hypogene copper deposition apparently ascribable chiefly to physicochemical, rather than purely structural changes. It would seem that downward mineralogical changes in these copper deposits gave criteria that indicated where mining operations were approaching the lowest limit of copper ore concentration.

Mining engineers and geologists that have had detailed contact with underground developments, particularly in the older districts, could add much to existing written information by giving concrete examples showing what various factors actually did determine the bottoming of specific ore deposits. So, if we have the opportunity at some future meeting, may I suggest that we ask such men to bring concrete evidence on the question, including vertical sections or three-dimensional drawings illustrating the conditions? There are numerous variations and I believe we have not assembled the evidence as much as we should. We have a great deal of evidence but we need a synthesis of it.

T. M. BRODERICK

It is one thing to recognize that the ore body has given out and hence in effect the roots have been reached, and another to say what the conditions have been that caused the decline in values.

There are two examples of mines having been bottomed in the Michigan copper district and we went down in the closing days to try to see just why they were bottomed.

In the upper levels of these mines the mineralization was in a thick, permeable, fragmental type of amygdaloid. At the bottom, where the mineralization played out, the ratio of that thick, permeable amygdaloid had decreased and most of the drifts were in a tighter, less permeable type of rock. Maybe that was the answer. On the other hand, we think that those particular mines may have had copper introduced by a series of feeding fissures swinging into the lode from the footwall. As the mine was deepened, one after another of those feeders was passed and perhaps finally the mine workings have passed too many of them, and the mineralization then has given out because it was below several feeders and there were not sufficiently numerous feeders below the bottom of the mine to give enough mineralization to continue downward.

If we do not like those two explanations of the root having been reached, we have still a third. There seems to be a zoning of mineralization in the copper district and it so happens that these mines were in the highest temperature zone that is recognized and perhaps the copper gave out not because of the two physical conditions that I mentioned but because the point where conditions favorable for copper deposition had been reached; that is, the bottom of the mine was too deep in the zone of copper deposition for further commercial mineralization.

There specific ore bodies were bottomed and there was ample opportunity to go down and make examinations, and yet three possible explanations of why the ore bodies gave out were made.

In the Michigan copper district, one of the earmarks of approaching bottom is the appearance of certain minerals that have come to be recognized as of higher temperature origin and hence belonging to the deeper zones. For instance, copper sulphides and arsenides begin to appear in greater amounts in the higher temperature zones and there are accompanying changes in the gangue minerals and the type of rock alteration. Some of the stopes in these mines in the higher temperature zone have considerable chalcocite. A little bornite and chalcopyrite appear with some specularite, and very rarely quartz pyrite veins cut the lode. Thus we are led to the speculation as to whether the native copper mineralization might yield in part to copper sulphide and finally to barren quartz pyrite mineralization in depth.

J. M. Boutwell*

The discussion this afternoon has been very interesting. I just mentioned to the Chairman that so far most of the discussion has been by men engaged in academic work, and I thought of the world of contribution made on ore deposits by men of the Geological Survey. I wonder whether the geologists in the academic field are more active or whether their tongues are better trained.

Before such symposia develop further, I mean next year perhaps, it will be very wise to define the essential terms so as to know what we are talking about. When we say "structure," what do we mean? When we say "roots," what do we mean? That will eliminate vagueness and we will get a good deal further. The custom in mining litigation of agreeing in advance to take certain meanings from certain words might be adopted to advantage in our future symposia to the end that statements be directed toward accepted defined issues.

George B. Langford

The finding of criteria to determine the bottoming of an ore deposit is of utmost importance, but the using of it must be done with the greatest of circumspection.

In many pre-Cambrian deposits it is evident that below 2000 ft. in depth the minor structures weaken and die, and so does any ore associated with them. It is to be assumed therefore that the major structures will follow along the same course. To my mind, one of the criteria of major importance is to watch for the weakening of the ore-controlling structures, or some changing condition that will cause the structure to cease to be ore-bearing. There are an infinite variety of conditions that might bring about either of these changes, and it is the duty of the mining geologist to solve these for his particular deposit.

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* Consulting Mining Geologist, Salt Lake City, Utah.

Changing of the vein minerals may be an advance notice of reaching the bottom.

The only use that can be made of these criteria is to advise the mine management whether they should explore the depth below the mine workings hopefully, or with a minimum of expenditure. I do not think our knowledge has reached the point where we can definitely say that a mine has bottomed unless it is obvious to everyone. The possibility of the existence of new ore bodies below the workings of a mine, unless experience in the particular field has already delimited the vertical depth of mineralization, is one of the intriguing problems in many of the mines in the Canadian shield. In many cases, or perhaps I should say most cases, it is too important a question to be decided on the opinion of any man. The best that mining geologists can do yet is to caution the management against too great expectations if the geological criteria point toward a bottoming of the ore deposit. To be dogmatic in such a case is to invite disaster.

EDWARD WISSER*

An attempt to answer this question when it was first propounded suggested to the writer some thoughts on the nature of criteria and the interrelations between facts of observation and theories to explain them. The conclusion was reached that criteria of observation indicating the bottoming of ore exist in nearly every camp, but that the use of such criteria must go hand in hand with regional study, directed especially toward the deciphering of the sequence of events that took place at and near the period of mineralization. These ideas appear in a paper already published.[23]

The following field criteria related to the bottoming of ore deposits serve to break the writer's own rule: certain physical features that seem to typify the majority of epithermal precious-metal vein deposits are listed regardless of whether the writer thinks he can explain them or not. The fact that these features are so nearly universal makes it likely that their repeated appearance is ascribable to something more than coincidence, and results from certain fundamental laws of vein formation that we may some day succeed in formulating.

These criteria apply exclusively to epithermal precious-metal veins, and the term "ore" means precious-metal ore alone.

Relative Distribution of Ore, Base Sulphides and Quartz

Base sulphides, in small or comparatively large amounts, usually characterize the veins discussed. Whatever their relative amount, they commonly show, in their distribution, the spatial relations to the precious-metal ore shoots and gangue bodies illustrated in Fig. 1.

Viewed in vertical longitudinal projection, the salient feature of most epithermal precious-metal veins is a body (or a number of bodies) of quartz or quartz and calcite. Base sulphides are sparse toward the top of this body, but they increase with depth to a horizon where they reach a maximum. The precious-metal ore shoots are found toward the top of the gangue body, and their hearts are roughly at the horizon at which the base sulphides reach a maximum. Below this horizon the base sulphides continue to the lowest explored depths with no universal tendency either to increase or decrease. (Exploration below bottoms of precious-metal ore shoots to a depth as much as 580 meters, at Guanajuato, Real del Monte and Sombrerete, Mexico.)

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* Consulting Mining Geologist, San Francisco, California.

A vein that carries base metals in commercial quantity at the heart of its precious-metal horizon may be expected to continue to do so to considerable depth below the bottom of precious-metal ore. But there appears no reason, judging by actual results of deep exploration, to suppose that a precious-metal vein carrying but small amounts of base metals at the heart of its ore zone shall turn into a base-metal mine at depth.

Applying these facts to the question at hand: with most epithermal precious-metal veins, there is a single zone of ore body expectancy, appearing as a roughly horizontal band in longitudinal vertical projections of the veins. The bottom of this band may be recognized by the fact that the vein there "looks splendid but doesn't run"; i.e., the gangue and base sulphides persist but the precious-metal content has suddenly dropped. This habit is perfectly or roughly shown in the following districts: Pachuca, Guanajuato, Tayoltita, Zacualpan, El Oro, Sombrerete, all in Mexico, and Telluride, Colorado. The list is far from complete.

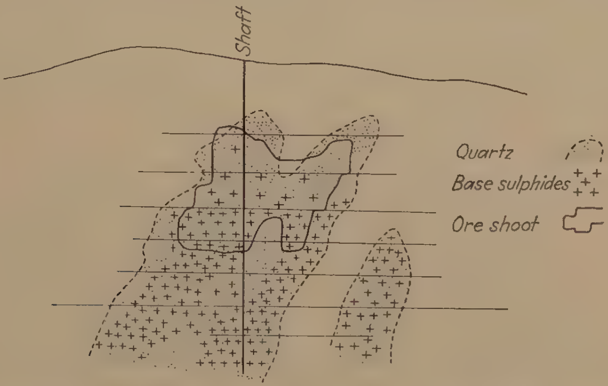

FIG. 1.—LONGITUDINAL VERTICAL PROJECTION OF AN EPITHERMAL PRECIOUS-METAL VEIN SHOWING SPATIAL RELATIONS OF QUARTZ, BASE SULPHIDES AND ORE.

Changes in Vein Minerals

The writer distrusts changes in vein minerals with depth as criteria for the bottoming of epithermal precious-metal ore bodies. (Except, of course, the disappearance of the precious metals themselves.) Systematic study of variations of zinc-lead ratios with increasing depth fails to show the consistent increase in the proportion of zinc expected by zealous followers of the zonal theory, although such an increase is suggested for a number of districts. In general, areal zoning, seen in plan, is more evident than vertical zoning, seen in section. It is not surprising that true tendencies toward changes in mineral composition, masked within the limited vertical range of exploration in most mines by local reversals, should become plain in lateral exposures often covering a range measured in miles.

The caution with regard to metallic minerals applies to gangue minerals. A legend of more than one camp has it that ore bottoms where the nature of the gangue changes; e.g., from predominantly quartz to predominantly calcite. True for individual ore shoots, this generalization has been overextended. In most districts, the depth zone of ore body expectancy, as stated above, is a roughly horizontal belt seen on the longitudinal vertical projections of the veins. In many districts quartz and calcite are the chief gangue minerals, and within the depth zone that contains the ore shoots, quartz commonly is associated with ore, calcite with waste. As quartz diminishes and calcite increases, the grade of ore falls; but this change takes place as often along the strike as down the dip; within the zone where ore occurs, the spatial relations of productive quartz and barren calcite have but a local influence on the distribution of ore, and below that zone, quartz and calcite are equally barren.

Changes in Structure

Most known veins have been truncated by erosion below their original tops, but vertical exploration has covered a sufficiently great range on a sufficient number of veins to reveal certain characteristic changes in their structure that take place with increasing depth. It is even possible to classify epithermal precious-metal veins in two major groups on the basis of the kind of structural changes they undergo with depth.

The two groups that seem to account for the majority of such veins are: (1) Fault veins that commonly dip rather flatly and have steep dip-branches that usually leave the fault vein on its hanging-wall side. The classical example is the Comstock lode, but El Oro and Parral (Palmilla mine), Mexico, come to mind as well. An example of type 1 is shown in Fig. 2*A*. (2) Veins, usually but not always along faults, that commonly dip steeply, and whose branches are strike-branches that may leave the main vein on either its hanging-wall or footwall side (Fig. 2*B*). Among examples of type 2 are the north-south veins of Real del Monte, Mexico.

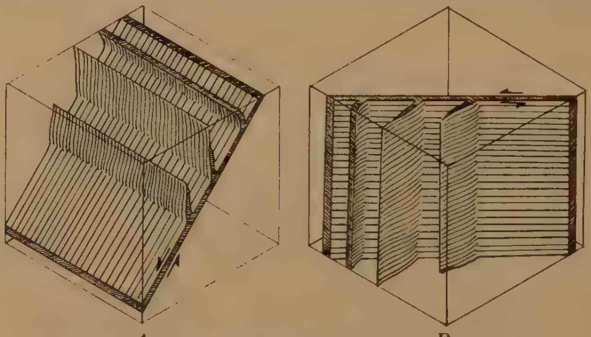

FIG. 2.—STEREOGRAMS OF BRANCHED VEINS.
A, Type 1, dip-branches.
B, Type 2, strike-branches.

The classification is thus based on the manner in which the veins branch. Fig. 2*B* is of course merely Fig. 2*A* laid on one side; many branched veins are oriented in intermediate positions. But the veins discussed do seem to group themselves in rather pronounced fashion into those approaching in orientation Fig. 2*A*, and those approximating in position Fig. 2*B*.

Type 1.—The main veins from which the branches diverge are usually mineralized normal faults, for the chief component of premineral or intramineral movement has been in the direction of the dip, and the hanging wall has moved down with respect to the footwall. The mineralization was usually closely linked in time with the faulting. Since the veins are epithermal, the fault movements involved took place close to the surface. It may be shown that many veins of type 2 never reached the surface existent at the time of their formation, for they do not reach the surface today; but it is significant that no evidence has been found to show that the veins along the normal faults of type 1 did not reach the surface at the time they were formed.

The steep dip-branches from these normal faults depend for their origin on their parent faults. They may be feather joints, torn open by frictional resistance to the movement down the dip of their main fault; or minor adjustment faults effecting differential settlement of the hanging-wall block above a major fault. Feather joints are especially likely to die out away from their parent fault before reaching the surface. Whether or not the *fractures* die out in that manner, the evidence shows that the open portions of such fractures that served as loci for veins persist for relatively short distances into the hanging-wall blocks of their parent faults. (Example, Comstock Lode.)

The ore shoots of the branched veins of type 1 are characteristically localized in these steep hanging-wall branch fractures. They pinch out going upward and bottom where the branch joins its parent vein. (Example, Comstock Lode.) Even where ore is not exclusively so localized, that in the branches is far higher in grade than in the main veins. (Example, El Oro district.)

Such a branched vein shows a treelike fracture pattern viewed in cross section. Multiple branches above coalesce at depth into a single trunk vein. A particular ore shoot in one of these branches bottoms where the branch joins the main vein. But the bottoming of the depth zone of precious-metal ore in general is likely to coincide with the horizon at which the lowest branch vein joins the trunk vein. This change from complex fracturing above to fewer, stronger fractures below marks the roots of ore at Zacualpan, State of Mexico, and Sombrerete, Zacatecas.

For the branched veins of type 1, therefore, coalescing of multiple veins above into fewer and stronger veins below forms a criterion for the roots of precious-metal ore.

Type 2.—Gravity may have caused the normal fault movement on a fault vein of type 1, but a horizontal shove induced the analogous movement associated with type 2, because the premineral or intramineral displacements on these faults took place in directions always close to the horizontal.

Normal faults like the vein faults of type 1 commonly die out along the strike in each direction. (Example, Comstock Lode.) The displacement is greatest, in general, about midway between the ends of the fault viewed in plan. Whatever force caused this faulting acted with maximum effect where the displacement was greatest, and its effectiveness died out progressively toward either end. Hanging-wall branches caused by the fault movement would be expected to reach their maximum development where that movement was greatest, and would be sparse or absent at either end where the movement was least.

Thinking of the branched veins of type 2 as those of type 1 "laid on their sides" (Fig. 2) one might expect by analogy that the horizontal displacement on these strike faults would decrease going upward, and that branching would decrease as the displacement decreased. The horizontal shove causing the displacements on the strike faults of type 2 probably acted in a way analogous to that of the force that caused the dip movements on the faults of type 1: at some horizon it acted with maximum effect, and its power to act decreased progressively from this horizon upward (and possibly downward as well).

The appearance of the branched veins of type 2 bears out these notions. In the upper horizons they are commonly single straight slips, and a decrease in the amount of horizontal displacement may sometimes be observed even within the limited vertical range of mine workings. With depth they begin to split, thus behaving in a manner exactly opposed to that of the branched veins of type 1. Feather joints, the orientation of which checks the observed direction of horizontal relative displacement (Fig. 2*B*) are perhaps the most common type of split, but intricate loop branches mark increasing depth as well. (Example, Real del Monte.)

The very strong strike faults of this group undoubtedly reached the surface existent at the time of their formation, for they are major regional features. They are also commonly barren of ore. The lesser strike faults and their branches often demonstrably did not reach the surface at the time of their formation, for some do not reach the present surface despite the fact that no postmineral capping covers the places where they should outcrop. (Examples: some north-south veins of Real del Monte; northeast veins, northern Pachuca district; probably the Pinguico vein, Guanajuato.)

As with the veins of type 1, fracturing and fault movements are closely linked in time with the mineralization. The epithermal precious-metal ore shoots are found in the lesser strike faults, mainly, and in branches of these faults or of the major faults. In general, the ore-bearing depth zone has its top not very far below the horizon at which these lesser fractures start to pinch out toward the surface. A description of a typical vein of this class will serve to make this clear.

At horizons above the top of the ore zone, the vein fracture is often a mere slip, and in some places this slip disappears entirely for a few feet along the projection of its strike, only to reappear. In this upper zone mineralization is commonly limited to manganese and iron oxide paint, but the walls of the slip are often highly altered, soft, bleached and talcy, so that slight, recent slipping along the fracture looks like important faulting, for the soft rock looks like fault gouge.

Sparse quartz starts to come in with depth, usually as a narrow stringer along the slip. The quartz increases rapidly in amount with depth and the top of the ore zone lies not far below the top of the quartz. Base sulphides are sparse here. The main slip persists, still straight and usually single; it is now one wall of the quartz vein. Fragments of wall rock included within the vein are sparse. Replacement, either of the few included fragments that are found, or of the walls, is at a minimum. The vein is well defined but still not very wide.

Base sulphides, sparse near the top of the precious-metal ore zone, increase with depth and reach a maximum, as has been said, at about the heart of that zone. Fragments of wall rock cemented by vein matter become abundant at this horizon; many are completely replaced by silica and sulphides. Here the vein attains its maximum width, and this width usually continues to the lowest explored horizon. The vein begins to lose its regularity. The main slip, which may have looked like a strong fault in the upper levels, may scarcely be seen at all, for the intensity of the mineralization serves to mask it. Branches increase in number; leaving and returning loop branches may carry ore as well as the main vein.

As the roots of precious-metal ore are approached, the complexity of the vein structure increases. Minor veins of this group, usually feather joint branches, often turn to typical quartz-cemented rock breccias near the roots of the ore. For these veins it would seem that the maximum intensity of mineralization lies above the horizon of the roots of ore, so that replacement of included rock fragments gradually decreases with depth, once the locus of maximum intensity has been passed. The breccia structure is strongly brought out. An extreme example is furnished by an east-west vein in Real del Monte. About 50 meters below the bottom of its ore the vein is an open fissure partly filled with boulders. Some interstices between the boulders are big enough for a man to crawl into. The boulders are coated with quartz crusts, but insufficient quartz deposited even to begin to fill the larger interstices. Above, in the heart of the ore zone, the vein is a quartz-cemented breccia but openings are scarce.

The major veins of this group, on the other hand, show fewer signs of a decrease in the intensity of mineralization below the roots of the ore. On the contrary, silicification and replacement are often intense at such horizons. The veins there may be ill-defined tabular zones of extremely silicified country rock impregnated with sulphides and traversed by quartz-sulphide stringers running in every direction. It is as if the intensity of the mineralization had overcome a deficiency of openings, although this deficiency is probably merely local. Curiously enough, "abras" or openings are found below ore in these major veins as well as in the minor veins mentioned in the preceding paragraph. But the abras of the strong veins are usually not unfilled interstices between the boulders. Careful examination of a number of them below the ore on the north-south veins of Real del Monte shows them to be actual rounded openings in the andesite. They may be lined with quartz prisms, but the latter can be knocked off. In a limestone district no one would hesitate to call these solution cavities. It would seem that a horizon exists in the veins of type 2 coinciding with the roots of the ore where there was not only a minimum of vein matter deposited but an actual tendency for solution of the wall rock at one stage in the process of mineralization.

Conclusion

I shall be content with suggesting one possible conclusion from the facts presented. Many others might be drawn. It may be significant that ore connected with the branched veins of type 1 is largely confined to the steep hanging-wall branches that probably never reached the surface at the time of their formation and mineralization. The veins along the main normal faults that are the parents of these branches probably did reach the then surface; such veins seldom carry high-grade ore. The vein fractures of type 2 that carry most of the ore in that group are those that probably never reached the surface existent at the time they were formed and mineralized, while the major strike faults of type 2 did reach the then surface and commonly are barren. Thus an apparent rule holds both for the veins of type 1 and those of type 2: vein fractures unconnected with the surface existent at the time of mineralization are favored loci for ore. The apparent rule suggests that trapping of ascending solutions may be a factor in the localization of epithermal precious-metal ore bodies.

General

S. F. KELLY

If a geophysicist may be pardoned for a few blunt words, I must confess that I am impressed by the vagueness and theoretical generalizations in the preceding discussion. The first problem, that of whether or not structural deformation is necessary for the migration of solutions, is essentially a geophysical question, because it is concerned with physical properties of geological formations. The second question, dealing with the influence of composition and permeability on ore deposition, is essentially a geochemical question.

The discussion on both aspects strikes me as in the nature of a post mortem. You have found out what it was that killed the patient, if he is dead, but nothing has been said about finding out what the patient's metabolic processes were when he was alive. Only one discussion this afternoon put the whole proceedings on such a basis, an experimental one, and that was Dr. Bain's.

Why not apply the techniques of the physics laboratory and the chemical laboratory and try some experiments to answer the question as to whether solutions migrate through cracks, or not through cracks? You ask about the chemical and physical characteristics of certain bodies within a limestone formation which will determine their suitability as hosts for ore or other introduced minerals. Admittedly, we do not know enough about ore minerals in solution to duplicate them in the laboratory, but at least experiments can be established to show what types of limestone will be replaced by what types of solutions, and what kinds of limestones will not.

I suggest, as a program for the continuation of this discussion, that something concrete be done toward applying the techniques of the physics and chemistry laboratories to the study of the questions that have been submitted to us here for discussion. Possibly some of that work has already been done some place, but if it has no one except Dr. Bain has drawn it to our attention this afternoon. I submit that any theoretical discussions can remain nothing but theory until they have a firm basis of experimental data as a starting point. Can we not stimulate the initiation of such experimental work, and come back to the subject at a future time when we have something to get our teeth into?

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Geology of the Getchell Mine

By Roy A. Hardy,* Member A.I.M.E.

(New York Meeting, February 1940)

The Getchell mine is a comparatively recent discovery in the old Potosi mining district, Humboldt County, Nevada, a district organized in the seventies and eighties, in which some prospecting was done in several metamorphic zones along a monzonite-sedimentary contact. The district had no production in the early days and no further work was done until the same metamorphic zones were prospected for tungsten (scheelite) in 1917 and 1918, when a few small lots were shipped. It again lay dormant until 1934, when prospectors investigated a large siliceous escarpment at one end of the old district where outcroppings were a prominent feature of the topography. Undoubtedly, during the early prospecting of the district, the outcroppings had been investigated for mineral, probably by panning, with negligible results because the gold later found is invisible in the concentrate and is refractory. A fire assay revealed the presence of sufficient gold to warrant development work.

The outcroppings were easily prospected by short tunnels having their portals in the siliceous material on the hanging-wall side, with a maximum distance to crosscut to the footwall of 135 ft., or a distance at right angle to dip of 60 to 90 ft. Development work, reaching a depth of over 600 ft. on the dip of the vein, was done by means of various crosscut tunnels, winzes and laterals. A churn-drill hole was also sunk, which intersected the vein at a depth of 1100 ft. on the dip. Sufficient development work of this character was completed by 1937 to justify the erection of a reduction plant to roast the sulphide ore and cyanide the calcine, and to treat the oxidized ore by straight cyanidation, to make a doré bullion for shipment to the mint. The erection of the plant was started that year and finished early in 1938, with a combined capacity of about 800 tons per day. It has operated continuously since erection and recently was enlarged to handle 1000 tons per day.

The vein dips with the slope of the mountain, and by stripping the hanging wall the ore may be mined by power shovel for several hundred feet below the outcrop. Thereafter underground methods will be necessary.

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* Consulting Mining Geologist.

Regional Geology

The Getchell mine is in the eastern foothills of the Osgood Range, about 1000 ft. above the floor of Kelly Creek Valley, which is a tributary of the Humboldt River Valley. The latter lies at an elevation of 5700 ft. above sea level. The mine is 16 miles north of the two transcontinental railroads, the Western Pacific and Southern Pacific, which use a common railroad station at Redhouse, on the Humboldt River. The nearest towns are Golconda and Winnemucca, 30 and 45 miles south and southwest, respectively.

The Osgood Range is a narrow north-south range typical of the Great Basin. It rises to its highest point in Adam Peak, which has an elevation of 8500 ft. The range has numerous small canyons and draws running easterly and westerly from the summit, with all the drainage reaching the Humboldt River.

The area is typical of the desert region in western United States. There is a moderate amount of precipitation; sage brush is the only vegetation, and temperatures range from about 100°F. in summer to zero for short periods in winter.

The range is composed of Paleozoic and Mesozoic sedimentaries, intrusive rocks presumably of Jurassic age, and intrusive and extrusive rocks of Tertiary age.

The Paleozoic sedimentary rocks consist of a conformable series of which the basal beds are schists of unknown thickness. Overlying the schists are quartzites several hundreds of feet thick, which in turn are overlain by several hundred feet of limestone, above which are shales about 1000 ft. in thickness. Within the latter is a thin-bedded horizon that forms the ore-bearing zone. In the vicinity of the Getchell mine the ore horizon is separated from the main monzonite mass by a variable thickness of the underlying limestone. The series has been strongly folded in a north-south direction.

The Mesozoic sedimentary rocks are exposed several miles north and east of the Getchell mine. They rest unconformably upon the Paleozoic series and consist of shales, conglomerates and quartzites having a total thickness of about 1000 ft. They are folded less than the Paleozoics, dipping at low angles to the north and east.

The most abundant igneous rock of the district is a monzonite, which occurs principally as a batholith occupying the center of the Osgood Range, the emplacement of the mass resulting in an uplifting of the invaded sedimentary rocks into an anticline. Subsequent erosion has exposed the monzonite. Numerous dikes of the same rock extend into the older sedimentaries, some being found in the mine workings cutting the vein bed. The latter are in some instances mineralized. The monzonite is probably of Jurassic age and its intrusion associated with the Sierra Nevada uplift.

The igneous rocks of Tertiary age consist principally of stocks, dikes and flows of andesite. Stocks and dikes of this rock are found in the mine workings adjacent to productive areas but while in places they are silicified and completely altered they have not been found to contain commercial mineralization, as have the earlier monzonite dikes.

The structural disturbance of the region to be noted began with the folding of the Paleozoic series in a north-south direction, paralleling the present range. The same forces resulted in the formation of fault shear zones, one of which was confined to the blocky to thin-bedded shale that later became the locus of the first silicification. This period of structural disturbance was followed by the intrusion of monzonite and, later, by the period of andesitic intrusion accompanied by the first period of mineralization. Following this was a period of tension faulting with normal displacements along all of the range, in which the valley, or hanging-wall, side moved downward. As a result of one such displacement, the mineralized shale bed, on the flank of the range, was brought out into sharp relief as an escarpment and a very prominent feature of the topography.

The second period of mineralization occurred in the late Tertiary and was of the fumarolic type characterizing the last stages of vulcanism. It resulted in the introduction into the previously silicified shale bed of arsenic in the form of realgar and orpiment.

ECONOMIC GEOLOGY

There are two types of deposits in the Getchell property. The first type consists of contact-metamorphic zones along the monzonite-limestone contact carrying commercial quantities of tungsten (scheelite) associated with molybdenite, chalcopyrite and pyrite in a gangue of quartz, garnet and epidote. These deposits have not yet been exploited.

The second type is a large body of siliceous gold ore occurring in the sheared shale bed and attaining a maximum thickness of 60 ft. The shale bed dips easterly at 40° from the horizontal and strikes N. 15° W. The brecciated and silicified material of the zone can be traced for about two miles before it is entirely buried by mountain wash. Considerable post-mineral inter-vein-bed movement has taken place, causing some overlapping. This intense faulting forms the hanging wall of the productive vein-shale-bed with the fault material in some places reduced to a gumbo gouge more than 30 ft. thick, all of which carries economic gold values.

The outcrop of the siliceous zone stands out boldly for about 2000 ft. in one area, and in this the silicification of the shale bed is complete and a secondary silica has been added. In other areas, at the surface, intense inter-vein-bed faulting has reduced the mineralized bed to a gougy material which has not resisted erosion and was easily covered by wash. The pattern of all the fault shear zones has not been completely worked out, as a second shear zone east of the mine workings and in the hanging-wall country, which was covered with wash, was recently discovered and is now being developed.

Ore Deposition

The fact that the monzonite dikes that intruded the vein bed are mineralized and contain gold is proof that the period of gold mineralization was later than the period of monzonite intrusion. The gold mineralization undoubtedly was associated with the early Tertiary period of andesitic intrusion. The deposits are of the overlapping epithermal-mesothermal type. The gold-free arsenic mineralization, in which the arsenic was deposited in the form of realgar and orpiment with other low-temperature sulphides, was of late Tertiary age.

The primary ore is a blue-black silicified shale containing vein quartz. It is fine grained and contains finely disseminated gold and gold-bearing sulphides. The gold is in part locked up in fine-grained pyrite, arsenopyrite and electrum, and is also present in the siliceous shell that forms the hanging wall of the ore body. Often it is coated with some foreign substance, which makes it metallurgically refractory.

The low-temperature arsenic minerals, realgar and orpiment, are distributed somewhat erratically throughout the vein bed. At times they occur as veinlets or bunches of solid sulphide. They are gold free, having been deposited later than that metal. The average arsenic content in the ore is slightly less than 2 per cent.

The outcroppings are oxidized for a length of about 2000 ft. and for a depth varying up to about 200 ft. The pyrite and pyrrhotite have been oxidized to limonite and hematite, and the sulphides of arsenic have been oxidized to a soluble form and removed by meteoric waters. As a consequence of these chemical changes, the refractory primary ore has been changed to an ore amenable to direct cyanidation.

The ore is continuous except at one transverse gulch where twisting and buckling of the vein bed has taken place, and in a second area where the shear zone was reduced to a comparatively narrow width.

Little can be said regarding the paragenesis of the sulphide minerals, which include pyrite and pyrrhotite, arsenopyrite, and the primary base-metal sulphides, sphalerite, galena and chalcopyrite, which were introduced at an early stage in the period of mineralization. Pyrite and arsenopyrite are both gold bearing, in small quantities. Stibnite, realgar and orpiment, low-temperature sulphides, were introduced at a late stage in the mineralization epoch. The copper sulphides, chalcocite and covellite, are probably of supergene origin. Minute quantities of selenium have been found in the doré bullion after melting of the cyanide precipitate.

Geology of the McIntyre Mine

By George B. Langford,* Member A.I.M.E.

(New York Meeting, February, 1938)

The McIntyre mine is in the Pearl Lake section of the Porcupine gold area. The rocks are Keewatin lavas intruded by quartz porphyries and albitite dikes of Algoman age. Gold-bearing quartz veins are found in the Keewatin rocks near the porphyry stocks. The whole area has been highly compressed by forces acting along a N. 20°W. line. These forces folded the Keewatin rocks before the intrusion of the Algoman rocks, and later schisted both the Keewatin and Algoman rocks. Vein fractures were developed after the folding but before the development of the schist by the compressive forces being locally broken up into couples. These couples were set up by the differential resistance to deformation of porphyries and basalts, and also by the competency of the dacites and incompetency of the tuffs and fragmental rocks. During the important period of vein formation, two zones were developed—an inner productive zone in which the quartz veins are ankerite-bearing and an outer barren zone in which the quartz veins are calcite-bearing. The vein solutions originated in the same magma that supplied the albitite dikes.

INTRODUCTION

The McIntyre mine, in the Porcupine gold area of northern Ontario, has passed its twenty-sixth birthday and has been producing gold since early in 1912. During this time approximately ten million tons of ore has been mined and over three and a half million ounces of gold recovered. This amount of ore would be sufficient to fill 2300 standard railway freight trains, each of 100 cars, and the gold produced, although only equivalent to a cube 5½ ft. to the side, would weigh approximately 100 tons, a load for three freight cars. Silver has been produced in the ratio of 1 oz. of silver to every 4.4 oz. of gold, so that the total silver recovery is in the neighborhood of 700,000 ounces.

The early history of the mine, like that of many others, shows that for several years it fought an uphill struggle for existence. One of the important features in winning this fight was the early recognition of some of the geological conditions responsible for the ore deposits, and the application of this knowledge in the search for ore and in the acquiring of adjoining properties. As early as 1913—only two years after the mine was opened—a geological department was organized. It has functioned almost continuously since that date and has demonstrated the importance

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of geological knowledge as an aid in mining in this area. In order to take full advantage of the recent advances in pre-Cambrian geological knowledge, a re-study of the entire mine was commenced in 1931, the results of which are incorporated here.

At that time there were approximately 50 miles of drifts and cross-cuts, as well as 55 miles of drill core, to be examined. The investigation included the mapping of all these workings, the relogging of all diamond-drill cores, and the examination of all accessible stopes. While this work was being done at the McIntyre, similar work was being done at the Hollinger, Dome, Vipond and Coniaurum mines. To the assistance of the investigators at those properties, as well as the Government geologists, the writer acknowledges his debt.

GENERAL GEOLOGY

The general geology and description of the rocks in the area have been given in published reports, and those interested in more detail than is given here can find it in references 1 to 6 at the end of the paper.

The rocks of the Porcupine camp are all pre-Cambrian. The geological column is as follows:

5. Keweenawan.	Olivine diabase dikes.
4. Matachewan.	Quartz diabase dikes.
3. Algoman.	Albitite dikes.
	Quartz porphyry (alaskite porphyry) stocks (the age of these intrusions is still controversial).
2. Timiskaming.	Conglomerate, greywacke, slate and quartzite.
1. Keewatin.	Volcanics with associated pyroclastics.

There are no Timiskaming rocks in the McIntyre mine, so they will not be discussed in this paper.

ROCKS

Keewatin

The Keewatin rocks form a series of effusives and associated fragmentals with some thin interbedded sediments. The flows can be subdivided into: (1) coarse and medium-grained rocks locally called greenstones and dacites, and (2) fine-grained and dense rocks locally called basalts. Further subdivisions as amygdaloidal and ellipsoidal can be used, but have been found to have no practical importance.

The greenstones and dacites are massive and usually homogeneous rocks. As seen under the microscope, there is practically no mineralogical difference between them, both having been dacites originally. The degree of alteration to secondary minerals has been severe, but not more so than is usual in these old rocks. In the hand specimens the dacites show easily recognized but small quartz "eyes," and by this means are differentiated from the greenstones. Leucoxene is common to both but usually is more plentiful in the dacites.

The basalts are essentially the same dacitic type but are finer in grain and usually show such structures as pillows, spherules and amygdules. These features are seldom seen in the dacites and greenstones, while fragmental tops are usually better developed on the dacites than on the basalts.

Greenstones and dacites often form continuous flows, but they also occur as isolated lenses which are gradational into basalts, and are merely local coarse-grained patches of the latter. This is an important consideration in working out the stratigraphy, for a great deal of effort has been expended trying to tie up such lenses into definite flows, but without success.

The stratigraphy of the Keewatin flows in the Vipond-Hollinger-McIntyre-Coniaurum area is as follows, the oldest being at the bottom (Fig. 2):

Gold Centre series. Greenstone flows with well defined fragmental tops.

Vipond series. Greenstones, spherulitic pillow lava and palagonite or fragmental flows. A prominent and continuous greenstone flow known as the "99" flow forms the base of the series.

Central series. Pillowed and amygdaloidal basalts with greenstone lenses.

McIntyre series. McIntyre flow and No. 6 flow (both dacites) with a prominent fragmental top on the McIntyre flow.

Northern series. Similar to the Central series.

Of these, only the Central, McIntyre and Northern series will be discussed here, as they only are ore-bearing on the McIntyre mine. For a description of the Gold Centre and Vipond series, see the articles by Graton[3] and Dougherty.[2]

Central and Northern Series

The Central and Northern series are lithologically identical and are differentiated only because they lie on opposite sides of the McIntyre series. In the eastern end of the mine the later series dies out, and it is impossible to differentiate the Northern from the Central series. The names for these two series are adopted from the usage at the Hollinger. However, because of the anticlinal structure under Pearl Lake, they are in reversed positions. Both series are basalts with irregularly scattered greenstone and dacite lenses. The basalts often show pillows, amygdules and some spherules. Occasional patches of fragmental flow-top material are frequently found but nothing definite enough to be traced over any distance. Each series is made up of several flows, but so far they have not been mapped individually.

McIntyre Series

The McIntyre series contains two prominent and well defined dacite flows called the McIntyre flow and No. 6 flow. The former is the best preserved and in many places shows excellent sections consisting of a narrow chilled base—sometimes overlying carbonaceous slate, a wide coarse-grained phase, a wide fine-grained phase, a heavy fragmental top. The fine-grained phase carries many large spherules, the largest being 12 in. across, with an average of 5 in. Their usual appearance is a light colored ring, but gradations are found from the ring to the usual solid gray spherule, and also from the large spherules to the ½-in. size. This flow shows very little shearing except in the chilled base and fragmental top. In places well preserved and undeformed pentagonal jointing can be seen. This flow was used as a horizon marker in working out the Keewatin structure.

No. 6 flow is neither as well defined nor as well preserved as the McIntyre flow. The base of it consists of a band of pillow lava basalt, which grades upward into dacite. The top ends rather abruptly under a thin and discontinuous fragmental top. As in the McIntyre flow, No. 6 flow is sheared only in its finer grained phases. One conspicuous feature of this flow is the association of carbon with the flow. This carbon is found in the basaltic base as narrow seams around joint blocks and pillows, but is found most abundantly in the fragmental top. Where faulted it develops into heavy, graphitic gouge. Formerly this graphite was thought to be of igneous origin because of its association with No. 5 vein. However, the carbonaceous material is associated with both contacts of the flow and throughout its extent, irrespective of the presence of vein material; it is also found elsewhere associated with narrow sedimentary bands, which lie along flow contacts, and it is now believed that the carbon is of sedimentary origin, having been deposited from Keewatin lakes or oceans.[3]

*Algoman**

Alaskite Porphyry.—These rocks (commonly known as quartz porphyry) form a number of disconnected stocks that occur more abundantly in the vicinity of the productive mines than elsewhere. The principal one in the Pearl Lake area is known as the Pearl Lake porphyry. In horizontal section it has a lenticular outline 5000 ft. long and 1500 ft. wide. This lens strikes N.76°E. and the dip is 83°S. In addition, the mass has a rake to the east of 45°. The shape and dimensions are maintained with remarkable fidelity to the bottom of the mine, a distance 1½ miles down the rake.

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* The age of the porphyries has not been definitely settled, but it appears from the evidence found on the McIntyre that these intrusives are later than the major period of folding, since they truncate the folded flows. The Timiskaming sediments were involved in this folding. This would make the porphyries of post-Timiskaming age.

The main ore zone on the Hollinger and McIntyre occurs around the west end and along the flanks of this intrusive. The other porphyries occur as satellitic bodies around the western end of the Pearl Lake mass but are neither as large nor as important as the latter, although they are the same type of rock. These porphyries originally were composed of albite with minor amounts of oligoclase and possibly orthoclase, quartz, and minor amounts of some ferromagnesians as biotite or hornblende. They are now almost completely altered to sericite schists on the upper levels, but below the 4000-ft. horizon they show a marked tendency to be less highly altered. Occasionally the basalts near the porphyry contain migratory quartz phenocrysts, which produces the effect of a gradational contact from Keewatin basalts to Algoman porphyries.

Albitite Dikes.—Intruded into the Algoman porphyry and Keewatin lavas are a well defined series of dikes. They are cut by the veins, so their age is definitely established between that of the porphyries and the veins. The dikes are found chiefly on the north side of the Pearl Lake porphyry from the 2000-ft. level to the 5375-ft. level, and they vary in width from 2 to 15 ft. and in length up to 2000 ft. They do not show the same degree of alteration or schistosity as the porphyries. They are holocrystalline rocks and consist of sodic plagioclase, interstitial quartz and a little biotite altering to chlorite. A most outstanding feature of them is the inclusion of holocrystalline rock fragments made up chiefly of sodic plagioclase, microperthite, some microcline and subordinate quartz. These inclusions are the size and shape of goose eggs, are well rounded and usually show pronounced reaction rims. They are thought to have come from a deep-seated and brecciated mass and to have been partially assimilated during transportation.

Matachewan and Keweenawan

Both quartz and olivine diabase dikes occur on the property but they have no economic significance. They vary from 2 to 60 ft. in width, strike roughly north-south, and some of them extend vertically from the surface to the 5375-ft. level. They cut the veins but there is no displacement along them.

STRUCTURAL GEOLOGY

The unraveling of the intricate tangle of the Keewatin lava flows is a relatively new phase of geology, and one that is destined to play an increasingly important role in the understanding of ore deposits in these ancient rocks. The first successful attempt to differentiate and trace individual Keewatin flows in Ontario was made by the staff of the

Ontario Bureau of Mines in 1918.[7] This was followed by Wright[8] in the Black River Area and Burrows[1] in the Porcupine area. These men were able to duplicate and extend the earlier work, and thus demonstrate that the Keewatin could no longer be considered "a hopeless complex devoid of any regular sequence."

Since then the Government geologists and the mine geologists have, with more or less success, been working out the local stratigraphy of the Keewatin flows. In the Porcupine camp it has meant carrying on the work that Burrows started in 1923, and, beginning from his generalities, to solve the local structures and find the relationship they bear to the ore deposits.

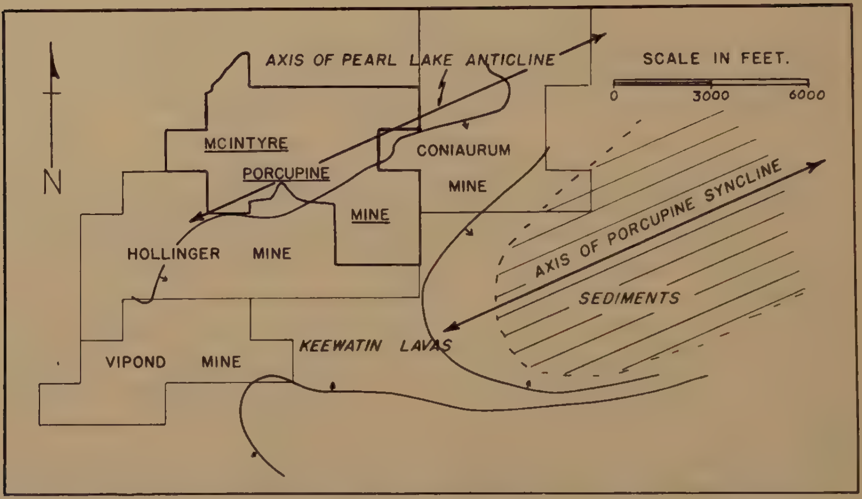

Fig. 1.—Producing gold mines and general geology in Pearl Lake section of Porcupine area.

Full black lines represent Keewatin flow tops and arrows show direction in which they face. Sediments include both Keewatin and Timiskaming sediments. Porphyry bodies not shown.

The general structure of the Porcupine area, as determined by Burrows, is a syncline whose axis strikes N.65°E. with a plunge to the east. The center of the trough is occupied by Timiskaming sediments and the flanks by Keewatin lavas, except in the western half of the area, where the sediments have been completely eroded (Fig. 1). The syncline continues to the west of the Porcupine area, but with a reversal of plunge, so that the structures all plunge to the west.[9]

In the Porcupine area, small folds occur on both flanks of the syncline. One of these passes through the main ore zone on the Dome mine, while another occupies a similar position in the Pearl Lake area. These structures have been responsible for the localization of the ore bodies in these main productive areas.

The folding in the Pearl Lake area consists of an anticline, called the Pearl Lake anticline, and a syncline lying north of it. The parallelism that exists between the axes of the Pearl Lake anticline and the large Porcupine syncline has led to the belief that they are complementary folds, the smaller one forming a drag fold on the flank of the larger (Fig. 2). This drag fold passes through the McIntyre mine (Fig. 3). Towards the west end of the mine the folds are well preserved and clearly identified as a syncline and anticline. Towards the east they become cut up by porphyries until near No. 11 shaft only the northern limb of the anticline remains. The porphyry bodies occupy axial positions in the folds, and it is believed that lines of weakness developed along the axial planes of these folds and were responsible for the location and shape of the intrusives.

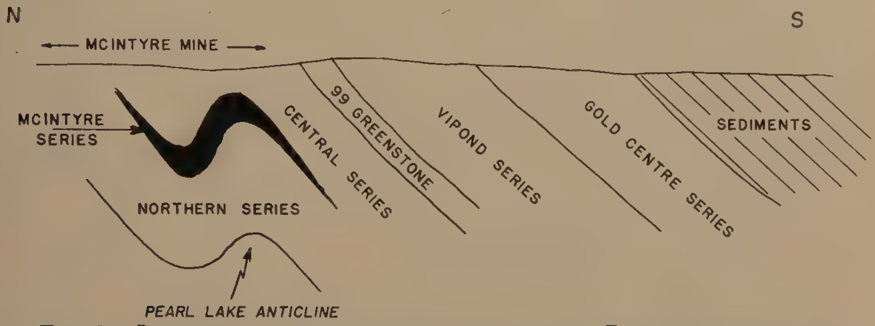

FIG. 2.—IDEALIZED SECTION ACROSS NORTH LIMB OF PORCUPINE SYNCLINE. On right are sediments occupying center of synclinal basin, and following them to north or left are various series of Keewatin lavas. No porphyry bodies are shown. Because of idealized nature of sketch, no scale is shown.

These structures were formed by a compressive force acting along a line a few degrees west of north.* This force was operative over a great length of time and was of orogenic magnitude with periods of quiescence and activity. The first effect of this disturbance was to throw the rocks into a series of folds such as now exist. During this folding, zones of weakness were developed along the axial planes of the minor folds, and into these zones of reduced resistance molten rock was forced to form the porphyry stocks.

The compressive forces renewed their activity following the porphyry intrusion, and the pressure was sufficient to cause rock failure and the development of schist. Before the development of foliation, however, minor adjustments were taking place, owing to the varying compressive strengths of the different rocks involved—i.e., porphyry, dacite and basalt. The result of these minor adjustments was the formation of fractures, which later were filled as veins.

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* An earlier formed anticline crosses the Hollinger and Vipond mines and is described on page 8 of Graton's article.[3]

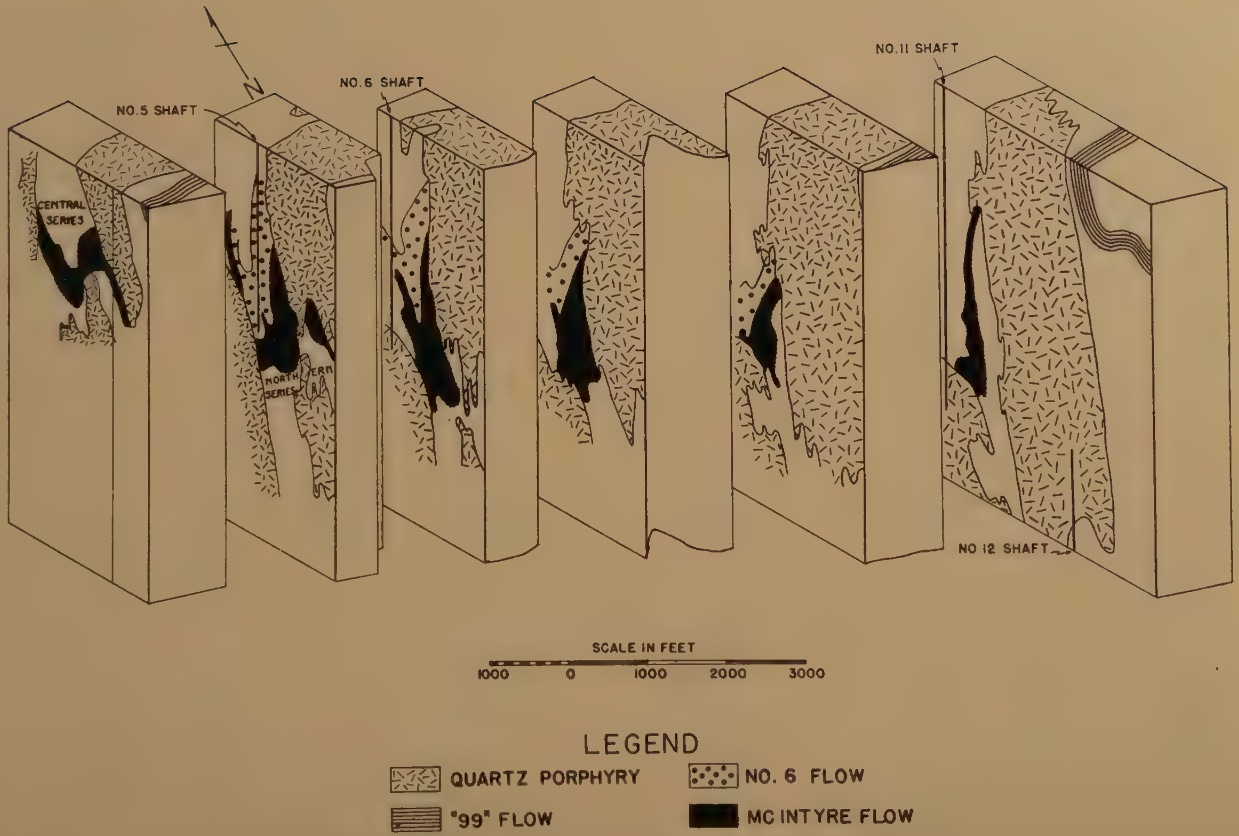

Fig. 3.—Block diagram of McIntyre-Porcupine mine.

Following the development of the vein fractures, compression continued until rock failure ensued, resulting in the production of belts of highly sheared rocks with intervening areas of moderately sheared or unsheared rocks. In general, the altered porphyries and fine-grained lavas were rendered more schistose than the large dacites. All degrees of foliation exist from undeformed rocks to paper schists. The strike of the schist is N.68°E. and the dip practically vertical. The axis of greatest deformation in the schist plane is inclined at 45° to the horizontal, so that original flow structures, as pillows, amygdules, spherules, etc., are elongated with their long axes dipping at 45° in a N.68°E. direction.

Early vein formation and the intrusion of the albitite dikes took place before the shearing was completed, but the main period of vein formation was later than the shearing.

Faulting took place before, during and after the folding and shearing. Pre-ore faults exist but are of no economic significance. The vein fractures are not considered to be faults, for there is no evidence of movement along these fractures. Faulting continued up to post-Glacial time (ref. 1, p. 42). The faults that displace the veins are all later than the diabase dikes. The strike of these faults is about east-west, and the dips vary from flat to 75° either to the north or south. The movements are usually reversed, the only normal movements known being of the magnitude of 5 or 10 ft., while reverse movements as great as 100 ft. are known. There are no faults of any importance below the 2000-ft. level.

Rock Alteration

All the rocks of the area, with the exception of the albitite and diabase dikes, have been profoundly altered. This has taken place on a regional scale and is not to be confused with alteration by the vein-forming solutions. Five types of alteration are found in the mine: (1) carbonatization, (2) chloritization, (3) sericitization, (4) silicification, (5) steatitization. They are given in decreasing order of their abundance. In general, the Keewatin lavas may show any of the types, while the Algoman porphyries have suffered only from types 1, 3 and 4.

Carbonatization has taken place by the introduction on a large scale of calcium and magnesium carbonates with more or less iron carbonate. Where the latter is abundant the rocks have been altered into ankerite. The usual effect of carbonatization is to produce a gray or brown color, at the same time preserving the original textures. The carbonate content of such rocks may be as high as 25 per cent, and in such cases they often effervesce in cold acid.

Chloritization is probably the result of propylitization. The rocks so affected are varying shades of green, owing to the presence of chlorite, and often carry a sprinkling of pyrite cubes. In the chloritized rocks the flow structures and original textures are well preserved Some chloritization has taken place as a phase of vein filling but the location of such chlorite serves to differentiate it from the other type.

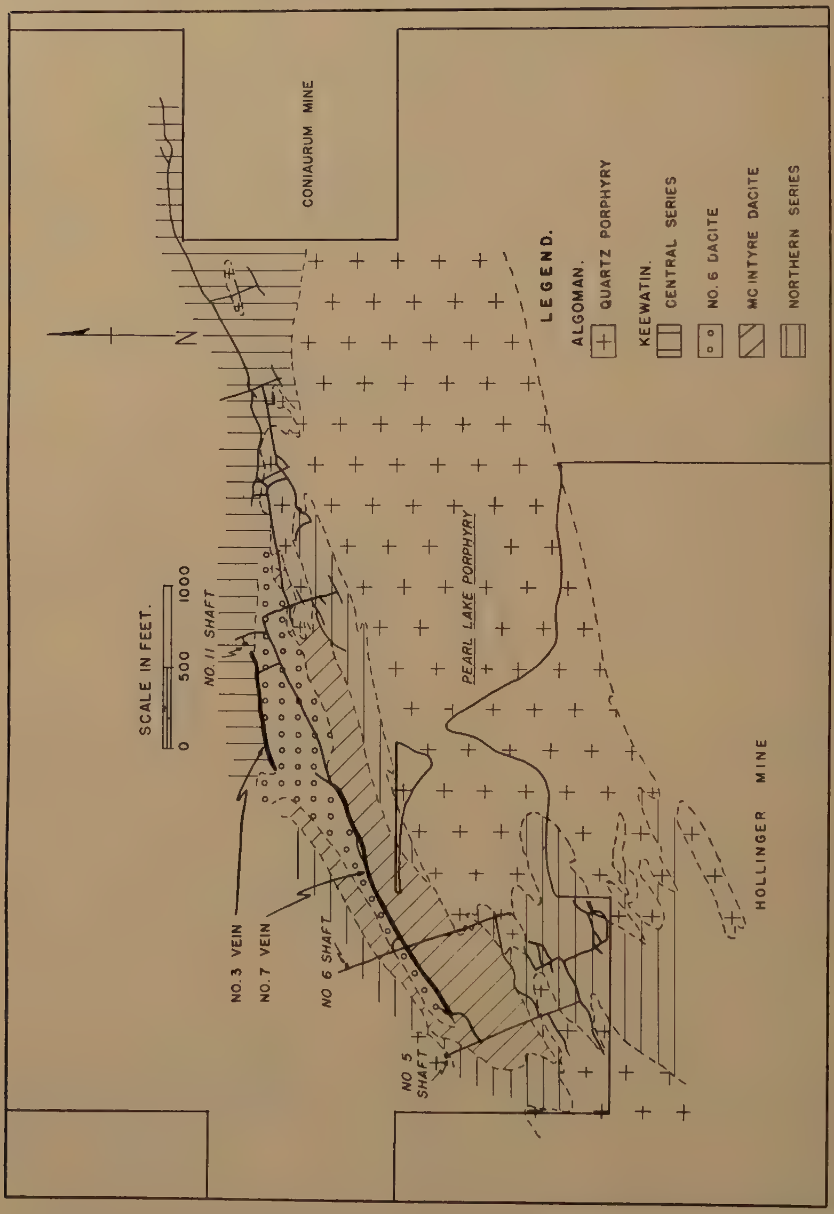

FIG. 4.—PLAN OF 2375-FOOT LEVEL, McINTYRE MINE.

Sericitization has affected the porphyries more than the Keewatin lavas. In practically all the porphyry bodies in the ore zone the feldspar phenocrysts are almost completely altered to sericite, and in addition a great deal of sericite is to be seen in the groundmass. These altered porphyries form the typical sericite schists of the area. Keewatin lavas close to the porphyries may be very sericitic, which would indicate that some at least of the sericite was introduced. Sericite is also a common vein mineral where it was introduced as a part of the vein filling. The vein sericite is younger than the sericite of the porphyries.

Both the Keewatin lavas and the Algoman porphyries have been silicified, although the lavas have suffered much more than the porphyries. The chief areas of this type of alteration are found along the north side of the Pearl Lake porphyry, but lesser areas exist elsewhere in the mine. The degree of silicification varies; some rocks have only a small amount of introduced silica, while in others all original structures are obliterated. From a microscopic examination, it appears that the rocks were first carbonated, and the silica replaced the carbonate. Even the most highly silicified rocks carry a much higher carbonate content than would be expected from an examination of the hand specimen. Typical silicified rock is dense, hard, uniformly fine-grained and gray in color.

Steatitization, or the development of soapstone, is confined to a small area of Keewatin lavas under the western end of the raking Pearl Lake porphyry, and below the 3500-ft. level. The rocks adjacent to areas of soapstone are usually very chloritic and grade over to soapstone. It is thought that the soapstone resulted from a special type of alteration confined to a small area under the porphyry, and not from the alteration of more basic flows or intrusives, as it has been impossible either to find any intrusive features or to recognize a flow more basic than any other.

All these types of alteration occur very irregularly as to size, shape and distribution. Very sharp boundaries are often found between altered and unaltered rock, but usually there is a gradational zone. So far no reason has been found to account for the distribution of the various types of altered rocks. The solutions that produced the alterations were not closely related to the vein-forming solutions. Probably they emanated from the same magmatic source, since sericite, carbonate and silica are common to both the regionally altered rocks and the vein fillings. The processes were not contemporaneous, as can be seen in the way veins pass from one type to another. All the various types of alteration preceded the vein formation.

Effect of Rock Alteration on Veins.—Carbonated and chloritized lavas are the usual and common phases of Keewatin. In the McIntyre probably 95 per cent of the lavas are so altered. In general, the lavas in the main ore zone are carbonated, while on the outskirts of the chief productive area chloritic lavas are in the majority. This association of ore and carbonated lavas was probably caused by the vein solutions coming up along the same line or lines of weakness as the earlier carbonating solutions, so that the same general area was affected by both. The association of carbonated rocks and ore is not a hard and fast rule by any means, for some good veins are found in chloritic rocks. However, it does hold in a general way, and in underground exploration the carbonated rock is looked upon as being kindlier than the chloritic rock.

Rocks that have been highly sericitized are not good ore carriers. When a vein passes into such rocks there is a marked diminution in values, which continues until the vein is below commercial grade. Because many of the porphyries are almost completely sericitized, while only a small percentage of the lavas are so affected, it was formerly thought there was some strange effect exerted by the porphyry on the vein solutions to prevent the precipitation of gold. However, it is now obvious that it was the sericite that prevented the gold from coming down, because sericitic rocks have the same effect whether they are porphyries or lavas. The reason is not so obvious, but the following is put forward as a possible explanation. Sericite was formed as a part of the vein-filling process, as well as a result of the regional metamorphism. In the former case the sericite was developed both in the vein quartz and as a selvage in the wall rocks on each side of the vein. The width of this selvage depended upon the penetrability of the rocks, but was usually from 1 to 3 ft. It is possible that the original vein solutions contained some element or elements that reacted with the wall rocks to form sericite, and the removal of these elements from the solutions allowed the precipitation of the gold. However, when the wall rocks were highly sericitized before the ingress of the vein solutions, the sericite-forming elements were unable to react with the walls, and perforce stayed as vein solutions, thereby preventing the precipitation of the gold.

Silicified rocks are poor ore carriers, although they are sometimes cut by veins. In most cases, the vein fractures feather out and die in stockworks, and the vein quartz has acted as a breccia cement, giving a tight structure with frozen walls. It effectively sealed the rock, so that when later auriferous solutions came along there were no openings for them to penetrate. Such veins often show good mineralization by nonauriferous pyrite.

So far our experience has not given us any information on soapstone as a possible ore carrier, but we do not look upon it with any favor.

THE ORE BODIES*

Quartz Veins

The veins in the Pearl Lake area occur in greatest abundance in the Keewatin lavas, which surround the Pearl Lake porphyry. They are much more numerous near the western end than on the flanks or the eastern end of this intrusive. In the McIntyre mine they strike N.65°E.

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* For a detailed discussion of the veins in the Porcupine district see Hurst.[4]

Dips are usually steep with occasional rolls. In general, the veins off the end of the porphyry are vertical, those on the north side dip northerly, while those on the south side dip southerly. These dips agree with the attitude of the Keewatin flows in which the veins occur.

The veins are found in well defined fractures, which may be long single breaks or a series of closely spaced and branching fissures, in the latter case often forming complicated stockworks. The vein material is largely quartz, which may form the entire vein; may form a series of more or less parallel veins, which branch and join to form a network of stringers; or may serve as a cement to hold together the slablike inclusions of wall rock, which are a conspicuous feature of many veins. Such inclusions, as well as a narrow selvage of sericitized wall rock, are usually well mineralized with auriferous pyrite. The vein quartz is never well mineralized and the bulk of the values in the quartz are as native gold. Free gold is occasionally found in the wall rock, but it is unusual, the values in the walls being in the auriferous pyrite.

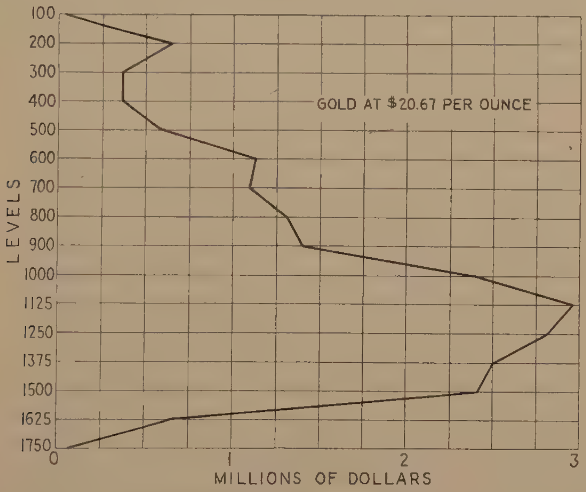

Fig. 5.—Production and reserves by levels, No. 5 vein, McIntyre mine.

Some of the large veins have been very productive. Fig. 5 shows the production and reserves for No. 5 vein. This vein extended into the Hollinger mine, where it was equally productive. Approximately 1,000,000 oz. of gold was originally contained in the portion of this vein that was in the McIntyre mine.

The veins vary a great deal both in length and width. The latter may be as great as 100 ft., although the average as mined is about 10 ft. In length the veins fall into two classes: (1) the long veins, from 500 to 2000 ft., and (2) the short veins, less than 500 ft. These two groups are more fittingly classified as: (1) veins on dacite contacts (long veins) and (2) veins in basalt (short veins).

In the dacite group are the strongest and most productive veins in the mine, such as Nos. 3, 5, 7 and 10. These veins are characterized by long stope lengths and great vertical continuity. They lie along the contacts of massive dacite flows and their limits both vertically and horizontally are definitely related to the attitude and extent of the flows. Fig. 6 shows this relationship in section. It illustrates how the veins extend from the porphyry contact to the bottom of the synclinal trough, terminating rather abruptly at both places. Nos. 3 and 5 veins are shown on the same contact but No. 3 vein lies east of No. 5 vein. In plan the veins cling closely to the same flow-contact positions (Fig. 4). This relationship between veins and flows is responsible for the easterly rake of the ore as the veins follow the plunging fold down to the east.

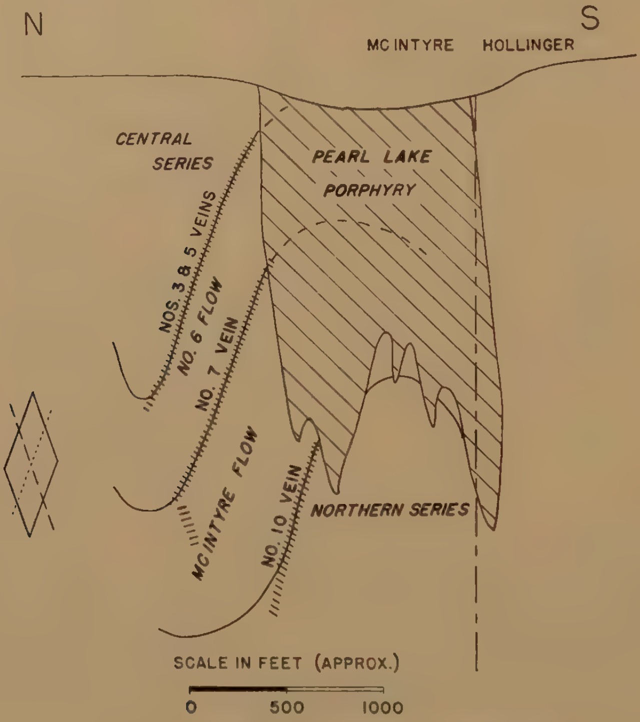

Fig. 6.—Veins on dacite flow contacts.

The veins in the basalts are lenses sometimes having dimensions as great as 500 ft., but usually less. They are found most abundantly around the ends of the Pearl Lake porphyry, in the large and homogeneous basalt flows of the Central and Northern series. Occasionally there are remnants of flow-top material associated with these veins, but usually they are found without any suggestion that they are on flow contacts. Fig. 7 shows a number of these veins as found on the 800-ft. level. The veins in the basalt do not show the same easterly rake as the dacite-contact veins.

Sulphide Ore Bodies

Most of the ore mined from the McIntyre mine has come from quartz veins; but a large and important tonnage has been mined from sulphide ore bodies. Such ore occurs where quartz veins pass from sheared and fine-grained rock into unsheared and coarse-grained rock and the mineralizing solutions were able to migrate to greater distances from the veins. The massive dacites of the McIntyre series offered an excellent opportunity for the development of such mineralization; consequently sulphide ore bodies are found as part of the veins that are associated with these dacites—i.e., Nos. 3, 5, 7 and 10 veins.

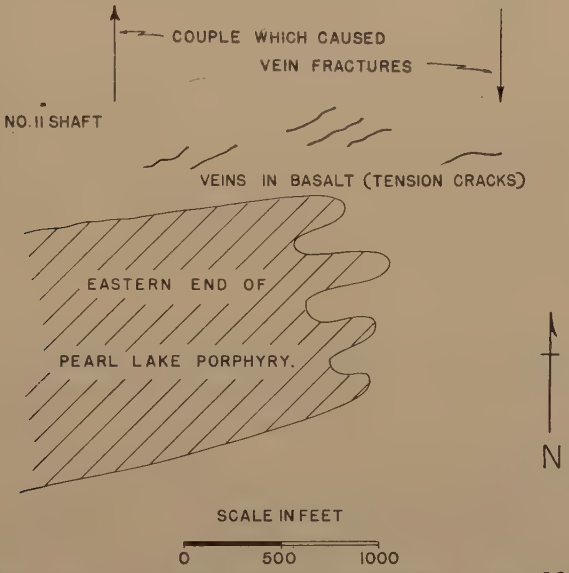

FIG. 7.—ECHELON VEINS IN BASALT, EAST END OF 800-FOOT LEVEL, MCINTYRE MINE.

Typical sulphide ore consists of pyritized and sericitized dacite. The pyrite forms from 5 to 15 per cent of the rock, and occurs as evenly disseminated cubes, which vary from 1/16 to 1/4 in. in size. The pyrite is auriferous and the grade of the ore runs about 0.5 oz. in gold, which is above the mine average. Visible gold is rarely seen in this type of ore. The dacites, which normally are dark green, are altered to gray by the sericite, and this color change marks the limits of the ore.

The shape of these ore bodies is very irregular. They are always formed around a quartz vein although the quartz vein forms an insignificant part of the ore. The mineralized dacite has the general shape of a wide zone bordering the vein, but often spreads out along joints and slips to form tabular bodies bordering these channelways. Such tabular bodies may join or branch, leaving irregular horses of waste. The width of such sulphide ore bodies varies up to 100 ft. Irregularity in shape is a characteristic feature of this type of ore.

The sulphide ore is a special development of the usual vein mineralization, although the sulphide bodies are quite different from the usual quartz vein. The latter always are bordered by from 1 to 3 ft. of wall rock carrying auriferous pyrite. This wall rock was schistose and relatively impervious, and the mineralizing solutions were unable to penetrate it to any distance from the quartz vein. However, where such veins passed from schistose walls to unsheared and relatively porous dacite walls, the solutions soaked out into the walls, forming pyritic ore bodies for great distances from the channelways.

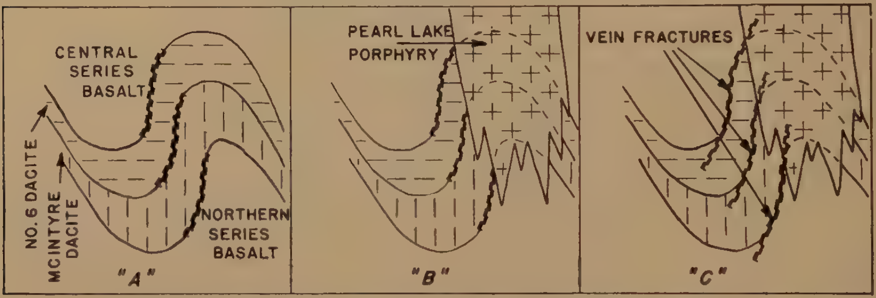

FIG. 8.—IMPORTANT STEPS IN DEVELOPMENT OF FRACTURES, WHICH LATER WERE FILLED BY LONG AND STRONG CONTACT TYPE OF VEINS.

A. Checkered bands emphasize zones where slipping occurred on contacts of massive dacites.

B. Shows position taken by intruding porphyry on axis of anticline and how it truncated tops of vein fractures.

C. Illustrates last phase of vein-fracture formation. Early lines of shear were extended for relatively short distances up into porphyry and down into synclinal trough. Contact type of veins now found occupying such fractures.

The sulphide ore bodies may be found anywhere along the above mentioned veins if they cut across dacites, but have their most important developments in the synclinal trough at the bottom of the veins, where the veins extend into the dacites (Fig. 6).

Development of Vein Fractures

The Pearl Lake area, subsequent to the intrusion of the porphyries, was compressed by forces acting along a N.20°W. line. The magnitude of these forces was large enough eventually to cause rock failure and produce a flow cleavage. During the early stages of this compression, but before the development of foliation, the differential resistance to deformation of dacites, porphyries and basalts broke up the straight-line forces into a series of couples, which in turn produced the fractures now occupied by the veins.

In the contact veins, the fine-grained contact facies of the flows were incompetent while the coarse-grained central portions were competent. Couples were set up, which produced a north-dipping active shear in the plane of the flow tops (Fig. 6). The south-dipping shear was inactive except at the bottom of No. 7 vein where the latter passes into the dacite. There a series of south-dipping lenses was formed. The fractures in the basalts of the Central and Northern series were formed at the same time. The fine-grained basalts, which occur in great abundance off both ends of the porphyry, proved to be less resistant than the porphyries and in the early stage of deformation couples were set up as shown in Fig. 7, and tension cracks were formed.

After the fracturing of the rocks, compression continued until flow cleavage was developed. The direction of the schist foliae is N.68°E., and generally speaking this strike is a few degrees different from the strike of the vein fractures. The result of this was that the vein solutions came into fractures in which the walls were irregular and ragged, and the solutions not only worked their way along the original fractures but followed the schist planes for short distances. In this way was produced the complex arrangement of quartz and wall rock so common to the Porcupine veins.

Vein Mineralogy

The mineralogy of the McIntyre veins is not complex. A few minerals are widespread and of economic importance; the remainder are mineralogical curiosities. In the former group are gold, pyrite, quartz, sericite, tourmaline, calcite and ankerite, while the latter group contains pyrrhotite, chalcopyrite, galena, sphalerite, tellurides, chlorite, albite, scheelite, siderite, dolomite, selenite and anhydrite.* Other minerals have been reported from the veins in the camp but have not been recognized in the McIntyre mine (ref. 1, p. 51; ref. 4, p. 121). The three phases of mineralization were:

1. Barren quartz tourmaline veins. This phase was widespread but the individual veins were small.
2. Main period of deposition of quartz, accompanied by gold, auriferous pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, tellurides, sericite, chlorite, albite, scheelite, ankerite, siderite, selenite and anhydrite. The veins of the early period were reopened and the later quartz often carries fragments of the former or forms ladder veins in the early quartz.

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* The graphite associated with No. 5 vein was formerly considered to be of igneous origin. It has been demonstrated recently by Graton that the graphite found in the Porcupine area owes its origin to the metamorphism of carbon, which was deposited as part of the sediments found between the Keewatin flows.

3. Barren quartz and calcite. This period was probably contemporaneous with No. 2 above, the quartz-calcite veins forming an outer aureole around the quartz-ankerite veins.

The quartz-tourmaline veins are seldom over 6 in. wide, but in some places, particularly in No. 22 vein on the lower levels, the wall rock was tourmalized, thus increasing the width of mineralization. These early veins were formed before the completion of shearing of the walls, and consequently have been highly deformed. Veins parallel to the schist were elongated into structures resembling strings of sausages—in many cases the "pinches" were later filled to form ladder veins—while veins normal to the schist were shortened by being highly contorted.

The veins of the main period of deposition were formed in the reopened early veins, as well as in other fractures. Fragments of the quartz-tourmaline veins are found in many of the later veins. The early veins never carry values on the McIntyre, and are mined only where they have been reopened and mineralized by the later vein solutions. The selenite and anhydrite of this period were late phases of the mineralization.[10]

The identification and differentiation of the last two phases of mineralization are important in underground exploration work. They are made by recognizing the carbonates; i.e., ankerite and calcite. The mineralogical zoning as worked out by Graton[3] for the Hollinger mine was found to apply on the McIntyre mine. Briefly, it is as follows: There is a central zone roughly concentric with the Pearl Lake porphyry, in which ankerite is present in the veins. Surrounding this is a zone in which calcite is the only carbonate in the veins. These zones are not regular in outline, but show a tendency to feather out into one another. On the contact there is often a gradational zone with both calcite and ankerite present. All the ore-bearing veins are found in the inner (ankerite) zone (although all veins in this zone are not ore-bearing), while the veins in the calcite zone are barren. It is the writer's belief that the veins in these two zones were formed at the same time, and that the barren calcite-quartz veins formed in the outer or possibly cooler zone while the gold-bearing ankerite-quartz veins formed nearer the foci of injection. This idea is supported by the facts that the two zones are quite separate and one is not superimposed on the other, and that there is often a gradational zone between the two.

The age relationships between the intrusives and the veins suggest a closer connection between the albitite dikes and veins than between the quartz porphyries and veins. Both the early quartz-tourmaline veins and the albitite dikes were intruded before the completion of schisting. The albitite dikes cut the quartz porphyries and are themselves cut by the main period of vein formation (the relationship between early quartz-tourmaline veins and albitite dikes has not been observed). Consequently, they were intruded before the veins and after the quartz porphyries.

The presence of albite in the intrusives and veins of the Porcupine area indicates that they are all comagmatic. It is thought that the quartz porphyries, albitite dikes and veins are derivatives of the same parent magma, but that the porphyries are separated by a long time interval from the other two.

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DISCUSSION

(George M. Fowler presiding)

E. Y. Dougherty,* Bellevue, King Co., Wash.—It is heartening to observe the growing understanding of the complex structural geology of this old and productive gold area, and to find oneself in agreement with so many of the findings and conclusions of the author. If the following comments stress alternatives and question interpretations more than they express unqualified agreement, it is because the more controversial questions are dealt with purposely in this discussion. In a thorough review of the paper, agreement would overbalance disagreement overwhelmingly.

Students of Porcupine geology will recognize vital differences in the author's visualization of the sequence of structural events and of the age of the porphyry as compared with some other interpretations, notably those of Graton, McKinstry et al.[11] The author pictures the establishment of the present folded structure in pre-porphyry time and the intrusion of the Pearl Lake porphyry into an already established drag-folded anticlinal zone, which had developed contemporaneously with the major folding of the Porcupine area. Since this folding involves the Timiskaming sedimentaries, it is concluded that the porphyry is of post-Timiskaming age. On the other hand, Graton, McKinstry et al. believe that the folding of the main period is later than the porphyry and that the porphyry is of pre-Timiskaming age.

In view of the truncation of the folded lavas by the Pearl Lake porphyry, as shown in vertical section in Fig. 6, and the disposition of the porphyry bodies in the anticlinal axial zones of the intruded rocks, discussed on page 157, the author seems justified in concluding that the porphyry was intruded into already folded rocks. Alternative views that the anticlinal structure was produced by porphyry intrusion, or that it resulted from localization of the anticlinal structure by post-porphyry folding near porphyry masses, are negatived by the field facts, which show the anticlinal structure to be continuous and the porphyry bodies disposed along the anticlinal zone to be discontinuous. A still further alternative view—namely, that although the present anticlinal structure was originally established in pre-porphyry time and influenced the localization of the porphyry bodies, there has been modification of the pre-porphyry structure by post-porphyry deformation (including a modification of pre-porphyry folding)—seems to me to have been treated inadequately by the author.

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* Consulting Mining Geologist.

[11] L. C. Graton, H. E. McKinstry and others: Outstanding Features of Hollinger Geology. *Canadian Min. and Met. Bull.* (Jan. 1933).

The author points out on page 157 that post-porphyry pressure caused rock failure and the development of schist. It seems inevitable that such pressure would cause folding also, *wherever the geologic conditions were suitable for folding.* Hence the question arises as to what extent the folding shown in Fig. 8 preceded porphyry emplacement and to what extent it developed subsequent to porphyry intrusion. Post-porphyry distortion has twisted the foliae of strongly schistose quartz porphyry in many places in the Porcupine area and has developed sinuous or serrated porphyry margins. Such distortions are in the nature of folding. In some zones it is clear that there has been thinning and thickening of formations and sharp folding, including drag folding; all accompanied or followed by fissuring, schisting and shearing and all later than porphyry. Such effects are variable in the same porphyry body; in different porphyry bodies; in porphyry bodies as compared with the intruded adjacent bodies of the intruded rocks and in different zones. It is conceivable that such differential deformation may have been produced without great modification of the broader features of the pre-porphyry regional structure, and this may be the key to the situation. Nevertheless, to one familiar with the intense schisting of the Pearl Lake porphyry, it is difficult to believe that adjacent folded rocks have escaped modification of their folded pre-porphyry structure.

The position of the Pearl Lake porphyry in the anticlinal axial zone of the major drag fold, as indicated in Figs. 6 and 8, is analogous to disposition of other porphyry bodies in the northeast extension of the same anticlinal axial zone in the Coniaurum mine. Consequently, there appears to be no doubt that this anticlinal zone has influenced the position of porphyry bodies, including the Pearl Lake porphyry. However, the relations of the porphyry to various structures, presented by the author, and to those in the neighboring Coniaurum mine, indicate that the Pearl Lake porphyry diverges somewhat from the anticlinal zone as it plunges downward in an easterly direction. This suggests that the Pearl Lake porphyry intruded the anticlinal axial zone at an angle and that there were additional controls on the attitude and form of this porphyry rather than lines of weakness along the anticlinal axial zone. In view of the strong deformation of the Pearl Lake porphyry and the closely approximate parallelism of the pitch of the long axis of the porphyry with the axis of greatest elongation in the schist planes in the porphyry and in the intruded rocks (pp. 155 and 159), it appears that the present form and attitude of the Pearl Lake porphyry is the result of post-porphyry deformation superimposed on its original form and attitude. Similar conclusions apply to other strongly deformed porphyry bodies of the Pearl Lake area.

In concluding that flow cleavage and strong shearing followed vein fissuring in time, the author advances a rather startling viewpoint. It is difficult to reconcile this time sequence with the truncation of schistosity (flow cleavage) by vein fissures, some of them with comparatively plane surfaces and the existence of strong fissures parallel to schistosity or at a small angle to schistosity. It is difficult also to explain vein fissuring that accompanied or followed distortions of the schistosity in time, if flow cleavage developed subsequent to these fissures. Furthermore, the author points out that post-porphyry pre-vein albitite dikes "do not show the same degree of alteration or schistosity as the porphyries" (p. 155). Therefore, unless the albitite dikes resisted the development of schistosity more than the porphyry (which does not seem logical in view of their analogous mineralogical constitution) some of the schistosity was not only developed prior to the vein fissures but also prior to the emplacement of the albitite dikes.

Because of the strike relations of the veins shown in Fig. 7 with the east-northeast strike of the major axis of strain of the rocks in the Pearl Lake area, the author's interpretation of these vein fractures as tension cracks hardly can be accepted without question. However, there are important deformed elongations of the Porcupine rocks transverse to the major direction of elongation in the area, and such transverse elongations might account for a tensional origin of these vein fractures.

Although the explanation on page 164 of low gold values in lodes in sericitic quartz porphyry and in other highly sericitic rocks is ingenious, one would like to have the problem studied by quantitative chemical and mineralogical methods. Data on the quantitative relations of gold to wall-rock iron and to lode pyrite and other lode minerals in highly sericitic rocks, as compared with relatively lowly sericitic rocks, would be illuminating.

The author points out the well-known concentration of abundant ore veins near the Pearl Lake porphyry and the closer time connection between post-porphyry pre-vein albitite dikes and the veins than between quartz porphyry and the veins. His conclusion that "the quartz porphyries, albitite dikes and veins are derivatives of the same parent magma, but that the porphyries are separated by a long time interval from the other two" strikes a logical balance between widely divergent views ranging from genetic explanation of the veins as direct magmatic derivatives from exposed quartz porphyry, through their explanation as derivatives of deep-lying unexposed parts of these quartz-porphyry bodies to derivation of the veins from a source quite independent of the magmatic source of the porphyry.

Geology of the Gold Quartz Veins of Cornucopia

By G. E. Goodspeed,* Member A.I.M.E.

(New York Meeting, February, 1939)

The Cornucopia gold quartz veins form a parallel vein system traversing metamorphic and granodioritic rocks. Field and petrographic evidence suggests that metasomatism has played an important role both in the emplacement of the granodiorite and in the formation of the veins. Structurally the veins appear to be related to the major tectonic features of the Wallowa Mountains and to be narrow shear zones rather than filled fissures. Petrographic studies indicate a complex history of formation starting from initial alteration along fractures or joints followed by recurrent fracturing and a quartz-forming stage, and closing with continued shearing and microbrecciation, which permitted the upward percolation of the later ore-forming solutions. The precipitation of ore minerals from these solutions formed ore shoots. Postmineral effects include the injection of Tertiary basaltic dikes, a slight amount of cross faulting, and some movement along the planes of the veins as well as oxidation.

Introduction

Cornucopia is in the southeastern part of the rugged Wallowa Mountains of northeastern Oregon. It was founded over 50 years ago following the discovery of its system of gold quartz veins. The major veins are roughly parallel and dip into the western side of Pine Valley, which drains the southern slope of the range. Previous operations had cut the upper portion of four major veins with two tunnels over 1000 ft. apart, when the present operating company drove a third tunnel, called the Coulter, at the level of the valley over 1000 ft. lower to intersect the most easterly major vein at over 6200 ft. from the portal.

General Geology of District

The oldest rocks in the vicinity are metamorphosed sediments and volcanics. These, for the most part, are presumably Mesozoic in age, although some black argillites outcropping along East Pine Creek are considered to be Permian.[1,2] These rocks have been deformed and metamorphosed in general to hornfels at the close of the Jurassic. The series was then invaded by a granodiorite batholith, the origin of which is

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* Professor of Geology, University of Washington, Seattle, Washington.

[1] References are at the end of the paper.

attributed by the writer essentially to metasomatic replacement rather than to the intrusion of a liquid silicate melt. The associated major veins have developed from hydrothermal action on planes of recurrent fracture. This region was then subjected to a general uplift and subsequent erosion. In some of the deeper canyons, such as that of the Snake River, the old surface is visible beneath the Columbia River basalt, and shows the development of a mature topography with a relief of about 3000 ft. The Wallowa Mountains are locally capped by basaltic lavas, and their present elevation is definitely due to faulting.

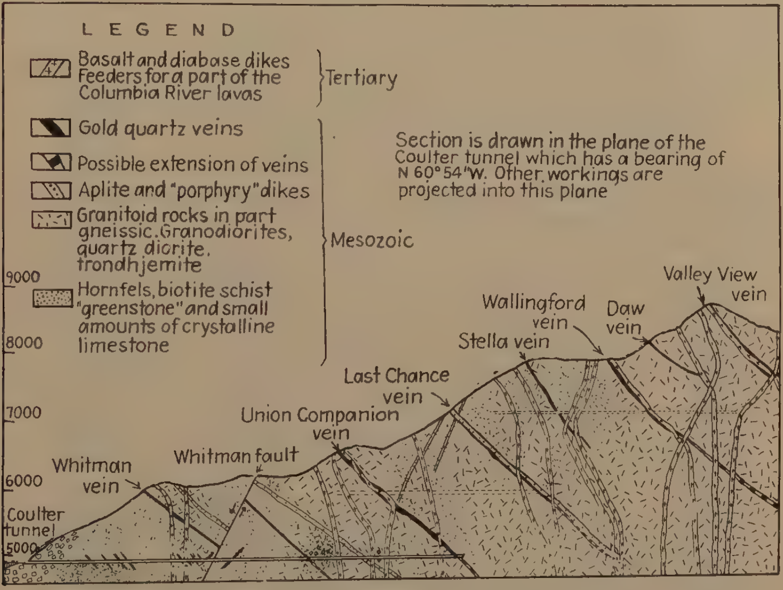
LEGEND
Basalt and diabase dikes Feeders for a part of the Columbia River lavas
Tertiary
Gold quartz veins
Possible extension of veins
Aplite and "porphyry" dikes
Granitoid rocks in part gneissic. Granodiorites, quartz diorite, trondhjemite
Hornfels, biotite schist "greenstone" and small amounts of crystalline limestone
Mesozoic
Section is drawn in the plane of the Coulter tunnel which has a bearing of N 60°54'W. Other workings are projected into this plane
9000
8000
7000
6000
5000
Valley View vein
Wallingford vein
Daw vein
Stella vein
Last Chance vein
Union Companion vein
Whitman fault
Whitman vein
Coulter tunnel

FIG. 1.—GENERALIZED GEOLOGIC CROSS SECTION, CORNUCOPIA, OREGON.

Characteristics of the Metamorphic Series

Although many facies of metamorphic rocks occur within a few miles of Cornucopia, hornfels, schistose hornfels, and biotite schists predominate locally. (Figs. 2 and 3.) Highly siliceous hornfels may contain small quartz porphyroblasts, while the more basic hornfels (locally called greenstone) are characterized by variable but conspicuous amounts of epidote, chlorite diopside and garnet.[3] Quartz-garnet-diopside veinlets are common in certain parts of the hornfels.[4] In texture most of the hornfels are very fine grained, but where extensive feldspathization has taken place, they approach the texture of a granulite (Fig. 4). Some of the transitional facies have the appearance of a porphyritic igneous rock, but the microscope clearly shows that the plagioclase crystals are porphyroblasts and not phenocrysts.[5] Most of the hornfels are

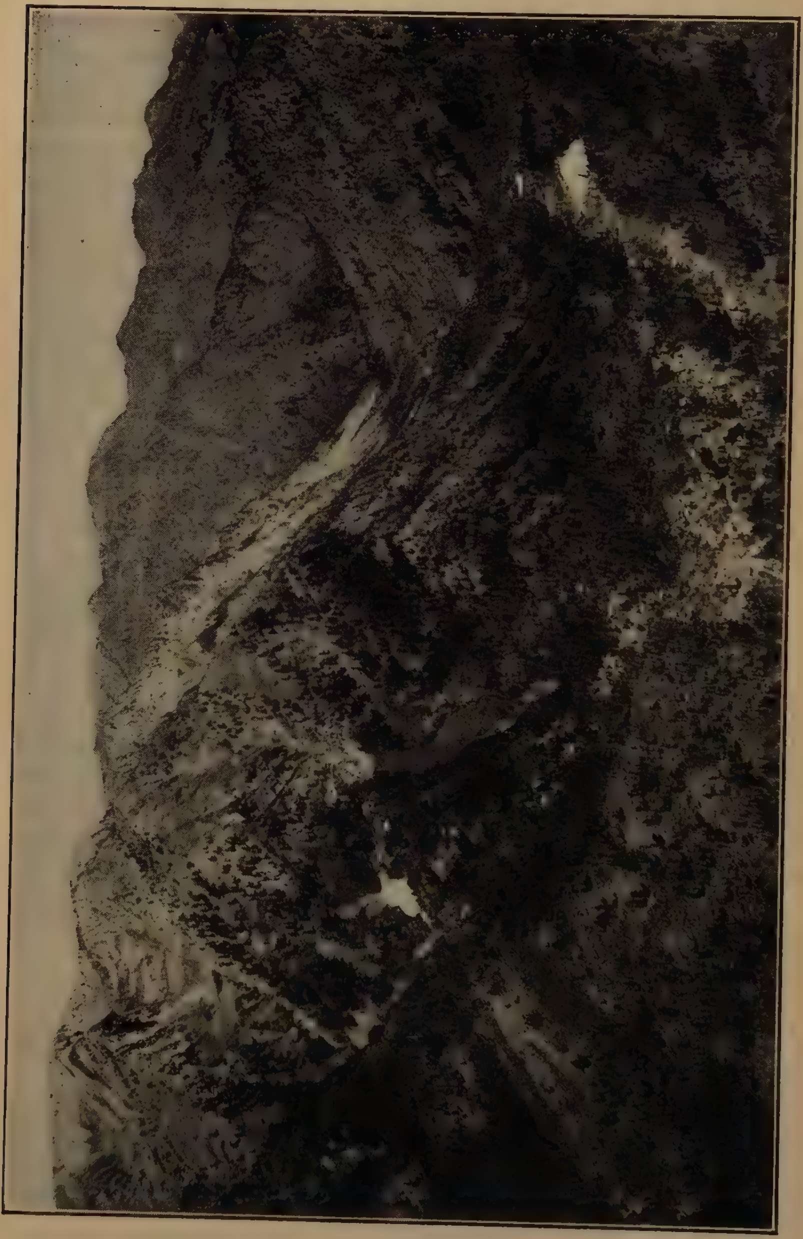

FIG. 2.—GENERAL VIEW OF CORNUCOPIA, OREGON.

Hornfels and biotite schist are the predominant dark colored rocks excluding the basalt dikes, which show in the photograph as irregular dark bands. Note scattered irregular patches of grayish rock transitional between hornfels and the light colored granodiorite.

impregnated with iron pyrite, so that they are stained a brownish color by surface weathering. Schistosity, many joint planes, and local brecciated zones testify to the shearing stresses accompanying the late Mesozoic orogeny. Field and microscopic evidence also indicates that the original material has been changed, in places very considerably, by additive metamorphism.

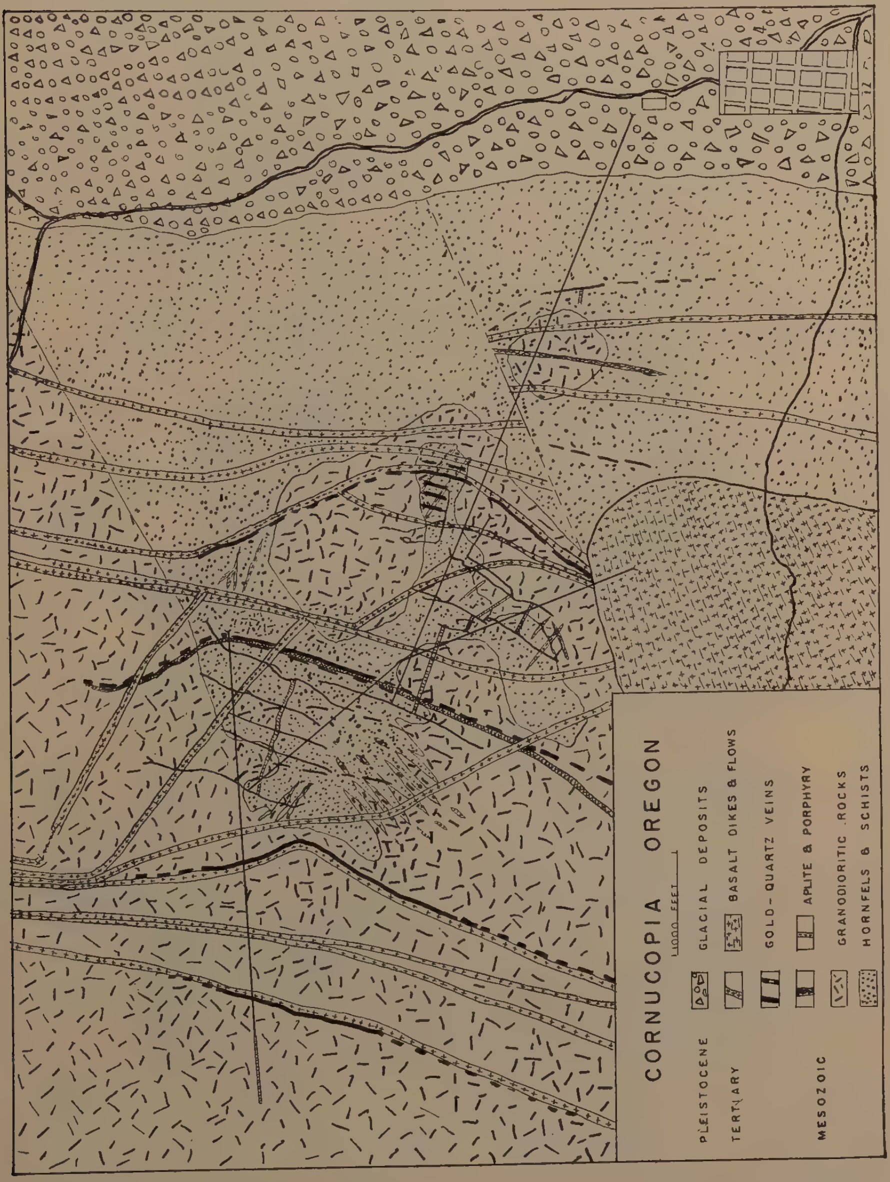

FIG. 3.—SURFACE GEOLOGY AT CORNUCOPIA.

Relation of Hornfels and Granodiorite

In the Coulter tunnel there are zones of brecciated hornfels that appear to have been partly replaced by granodioritic material in irregular block-like forms.[6] Here metasomatic action was apparently intensified in local patches of finely crushed material. The angularity of the granodioritic blocks was due presumably to the margins of the more resistant larger fragments of hornfels. The borders of these blocks are in part sharp and in part gradational into the hornfels. Some of the blocks exhibit veinlike extensions of the granodiorite into the hornfels, and some contain delicate undisturbed inclusions of hornfels, which still retain original structures. Alternative hypothesis of magmatic injection or of faulted granitic bodies are not in harmony with all the facts. The lack of crushing within the blocks, and the lack of chilled borders or evidence of flow structure, coupled with the positive evidence of crystalloblastic extension of plagioclase along some of the contacts, suggest the mechanism of metasomatism (Fig. 6).

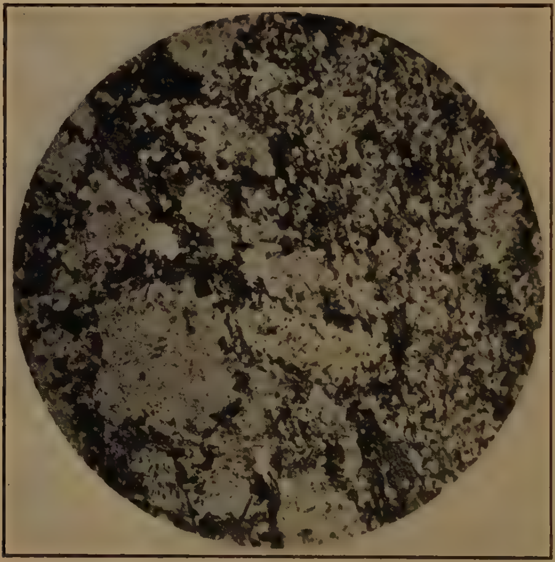

Fig. 4.—Partly feldspathized hornfels.

Although striking in appearance, such occurrences are not as common as replacement dikes and replacement breccias.[7] Such features might casually be interpreted as ordinary dilation dikes or as swarms of xenoliths that became included in a hot, liquid magma. However, they exhibit many characteristics that point definitely to a gradual process of granitization rather than to the solidification of a hot liquid melt (Fig. 5).[8]

At Cornucopia, transitional hornfelsic granodioritic facies are so common, and the field and petrographic evidence so abundant and conclusive, as to warrant the suggestion that most of the granodioritic rocks have been formed as the end stage of progressive metamorphism.[9] The usual interpretation for the emplacement of a granitic batholith is based upon the assumption that the granitic rock crystallized from a hot, liquid silicate melt or magma.[10] However, it has been shown recently that in

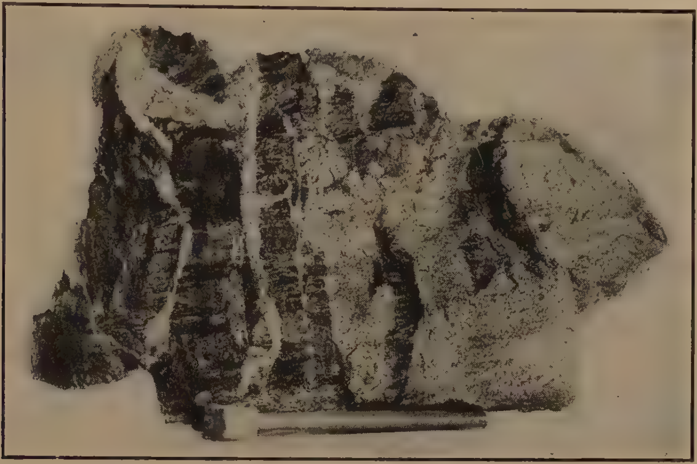

FIG. 5.—LARGE SPECIMEN FROM COULTER TUNNEL.

Note gradual transition from dark hornfels to light colored granodioritic rock. Numerous parallel stringers of "porphyry," of which the phenocrysts are in reality porphyroblasts accompanying an initial stage of metasomatic replacement while the phantomlike shadows of hornfels inclusions mark a later stage of granitization.

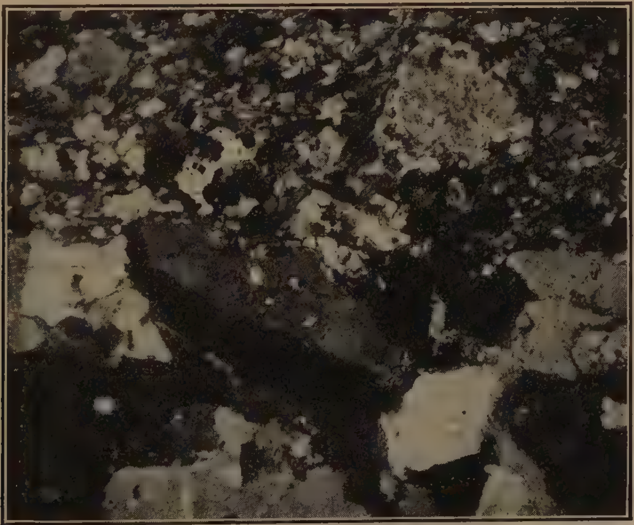

FIG. 6.—CONTACT BETWEEN GRANODIORITIC BLOCK (LOWER HALF OF CUT) AND HORNFELS.

Note incipient feldspar porphyroblast in hornfels and inclusion of hornfelsic material within and around feldspars of granodioritic block.

some batholiths replacement processes may play a most important role.[11–16] In England, also, the origin of certain plutonic rocks has recently been ascribed to metasomatic processes.[17]

Origin of Aplites and Quartz Veins

From the standpoint of the origin of ore deposits, the genetic relation of metamorphic differentiation instead of magmatic differentiation should be stressed.[18] Several years ago, it was noticed that some small quartz veinlets apparently were found as the product of the recrystallization of a xenolith.[19] The formation of quartz as a released mineral incident to recrystallization processes may perhaps give a clue as to the source of part of the quartz associated with the later hydrothermal solutions.

Regional field evidence indicates that shearing stress was prevalent preceding, concomitant with, and succeeding granitization. Some facies of the hornfels are veritable crush breccias and cataclasites. In some of these sheared rocks, fracturing, solution, replacement, and recrystallization have had varied sequences. In general the interlocking decussate texture of the granulites or the hypidiomorphic granular intergrowth of the granodioritic rocks does not appear to have favored the innumerable shear planes that characterize some of the hornfels and schist. Instead, these even-grained rocks have broken along either single planes of shear or narrow zones of very closely spaced shear planes.

The rise of hydrothermal solutions along these shear planes appears to have produced various effects. In the field, all gradations may be seen from mineralized fracture planes to quartz veins or aplite dikes. Hydrothermal origin has recently been suggested for some aplites in Ontario.[20] In like manner, at Cornucopia these dikes, even when of considerable magnitude, appear to be definitely formed by replacement rather than by magmatic origin. This is indicated by the fact that the dikes include locally undisturbed remnants of schist or hornfels, and have failed to cause an offset in the structural features of the wall rock. Petrographic examinations of the marginal contacts of the dike substantiate this conclusion, for the irregular penetration of the crystals of the dike into the wall rock indicates crystalloblastic encroachment.

The field evidence at Cornucopia strongly suggests that the gold quartz veins are genetically associated with the later or retrogressive phase of the intensive hydrothermal metamorphism to which the granodiorite is genetically related. They appear essentially to be due to replacement along lines of fracture that developed in the closing stages of late Jurassic orogeny. The quartz veins formed brittle zones of weakness, which controlled subsequent movements. The recurrent fracturing permitted the continued rise of the hydrothermal solutions.

Columbia River Basalt

During the Tertiary, and particularly during the Miocene, this region was subjected to profound tensional fracturing, and was traversed by many prominent fissures, which followed in part the existing planes of structural weakness. Through these fissures, many of which were from 40 to 50 ft. wide and several miles long, poured out floods of hot basaltic lava in a series of widespread flows known as the Columbia River basalt. The aggregate thickness of these flows was several thousand feet, enough to completely cover the old mature land surface. At Cornucopia the dike feeders for the basalt flows are especially well exposed and form distinctive surface features, particularly where the dark basalt is in striking contrast to the light colored granodioritic rocks. Since the dikes follow planes of weakness, their course has been controlled by the gold quartz veins, especially when approaching the old land surface. Near this surface they may also follow a system of conjugate jointing and so have variable dips. At greater depths, as shown in the lower workings of the mines, the dikes are more nearly vertical, indicating that the increasing load nullified the joint control.

Where the dikes intersect the veins at other than a right angle, the veins are offset because of the dilation of the dike fissure. Therefore, in development work it is in general necessary to drive across a dike at right angles to the strike of the dike. Since actual dike contacts may be irregular; the recognition of columnar structure at right angles to the dike wall is of considerable practical aid.

The Tertiary basaltic dikes at Cornucopia may be placed in two groups, an earlier one, which is diabasic in character, and a later one distinctly basaltic. The outcrops of the diabasic rocks show rounded surfaces due to spheroidal weathering, while the finer grained basaltic dikes appear to be more resistant. Columnar structure is also more evident in the basaltic dikes. It is not unusual to find compound dikes.

Although the temperature of the basaltic lava was probably about 1000° C.,[21] the extent of optalic metamorphism is not great. Probably the quickly chilled selvages acted as an insulating medium. However, where dikes of sufficient size were injected parallel to the gold quartz veins, the heat was sufficient to change pyrite to pyrrhotite. This is especially noticeable on some of the upper levels of the Union Companion vein. Along the bottom of a basalt flow, as exposed in the intermediate or Clark adit, detrital quartz from the Union Companion vein has been picked up by the quickly chilled lava. The wash from the vein may well have been in some old creek bed, since the alteration products suggest aqueous chilling.[22] Assay of this material shows some gold content, due to contamination.

Basin Range Structure

After the successive outpourings of basalt, this region was subjected to block faulting similar to that in the Basin Range. Some of these faults had displacements of perhaps as much as 5000 ft., and are reflected in the present-day topography.[23] Pine Valley is a typical fault valley and the fault-line scarps are evident.

A very well marked normal fault was observed in the Coulter tunnel. Its position indicates that the upper part of the Whitman vein is on the downthrow side and the fault plane probably cuts the vein just above the level of the Coulter tunnel. What appears to be the vein in the upthrow portion of the fault was intersected by the tunnel 4000 ft. from the portal. If this is the Whitman vein on the upthrow side of the fault (and petrographic evidence appears to substantiate the field observation) the movement along this fault plane has been about 800 ft. Although probably much greater displacements have taken place in this region, yet in the Cornucopia mines, with the above exception, the amount of postmineral dislocation as at present disclosed has been only a few feet.

After these presumably late Pliocene dislocations, the uplifted blocks were subjected to extensive stream erosion culminating in the Pleistocene with severe mountain glaciation. Numerous erosional and depositional features incident to alpine glaciers are to be found in the Wallowa Mountains. Many of the steep-walled U-shaped glacial valleys have afforded excellent geological cross sections, and at Cornucopia have exposed some of the gold quartz veins for a considerable extent along both their dip and their strike. The southern slopes of some of the mountains have a mantle of weathered material, while the deep cirques and glacial valleys have been carved in unweathered rock.

Weathering

Since the Pleistocene, the amount of surface rock weathering has been relatively slight except where there has been an abundance of easily decomposed minerals such as sulphides. Some of the hornfels have been stained brown by limonite derived from disseminated pyrite, and the outcrops of the gold quartz veins are oxidized. On most of the veins there is an irregular downward penetration of oxidation for several hundreds of feet and in some of the veins narrow oxidized zones are found at a depth of over 2000 ft. from the outcrop. The water courses formed by the sheared veins readily permit the draining of ground water from the surface, which is 1500 ft. or more above the valley floor.

The yearly precipitation at Cornucopia is about 45 in., a large part of which is in the form of snow. Although the soil mantle is meager, the numerous joints in the rocks provide ample opportunity for the downward percolation of the surface waters. Some of the joints become veritable water courses, as do also portions of some of the quartz veins.

General Field Relations of Cornucopia Veins

The Cornucopia veins appear to be structurally related to the major tectonic features belonging to the late Mesozoic orogeny. Of these the westerly dipping shear planes have exercised the principal structural control, although some of the smaller veins follow the subsidiary eastward-dipping complementary fissures. At Cornucopia the important veins, beginning with the most eastern one, are: Whitman, Union Companion-Red Jacket, Last Chance, Wallingford and Valley View. These veins are 1500 to 2500 ft. apart, and have in general a strike of N. 40° E., and a dip of 40° W. All the veins are irregularly lenticular, in some places very narrow, practically a gouge seam, and at others several feet wide. To date the greatest thickness has been encountered on the Union Companion, where several places show widths of from 8 to 10 ft. Some of the lenses in the Cornucopia veins are long and tabular, while others are more abrupt. Structurally these veins appear to be similar to the larger veins, but on a smaller scale.

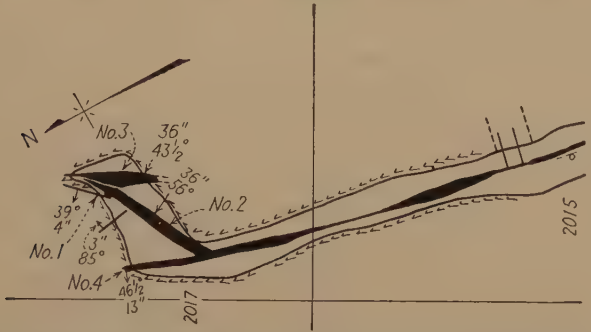

Fig. 7.—Offset in Union Companion vein 2000 drift north. Specimens 1, 3 and 4 exhibit microbrecciation while No. 2 does not. The connecting vein with an easterly strike (No. 2) probably represents a filled fissure while the main veins are of the cataclastic shear type.

Some of the Cornucopia veins, as now exposed by erosion and by mine workings, are entirely within the granitic rock, some are within the hornfels and schists, and others traverse remnant masses of these rocks in the granitic rock. Most of the upper workings of the Last Chance vein are in hornfels and schist; granodiorite is the prevailing wall rock in the lower workings. In many places this vein consists of two veins, one on the hanging and one on the footwall of a 30-ft. aplite dike.

The veins that have been developed along the strike for considerable distances commonly exhibit a sort of en echelon offset every 500 or 1000 ft. The offsets are usually about 20 to 30 ft., and at these points the veins become imbricated. These features were interpreted by some early observers as the ending of the veins. Some of the offsets are joined by short connecting veins. Such a condition was recently found on the north 2000 drifts of the Union Companion vein (Fig. 7). These connecting veins are in the nature of large gash veins and as such they represent filled fissures and apparently have not been subjected to extensive shearing.

From a structural standpoint all of the major and minor veins of Cornucopia appear to be in reality narrow shear zones. Slickensides, gouge and fractures both in the veins and in the contiguous wall rocks, as well as definite petrographic evidence of microbrecciation, prove that movement in the veins continued during the time of their formation, and contributed to the irregularity of the lenses.[24] Grooves in slickenside surfaces indicate that a distinct change in direction of movement took place during vein formation. The earlier slipping appears to be in the direction of the dip; some of the later grooves have a rake to the south.

Some of the Cornucopia veins are situated near the southeastern border of an irregular granodioritic mass and some are in nearly the central part of the granodiorite. This granitic mass is about four miles in a northwest-southeast direction and three miles in a northeast-southwest direction. The strike of the veins is parallel to anticlinal and synclinal axes in the older rocks of this part of the Wallowa Mountains. In the vicinity of Cornucopia there are a multitude of shear planes in the hornfels and schist as well as in the granodiorite, and the veins are parallel to these planes.

Some of the Cornucopia veins have parallel branch veins, which do not seem to have been sheared as much as the main vein. The veins of the Red Jacket mine that belong to the Union Companion system might be cited as an example of this branching. These branch veins were probably formed nearer the existing surface than the other veins. Under such conditions it might be expected that lessened rock pressure would favor the opening of parallel fractures and fissures in addition to the main zones of shearing.

The salient features of the field relations of the Cornucopia veins are shown in the generalized geologic cross section (Fig. 1). This section is constructed on the plane containing the Coulter tunnel with the Clark adit and the Lawrence tunnel projected into this plane. As shown in the section, an inclined raise was driven from the Clark-adit level to the upper levels of the Last Chance mine. A winze has also been driven for 100 ft. or more below the Coulter-tunnel level on the Union Companion vein. Both the Union and Last Chance veins have been drifted on for several thousand feet on various levels.

Formation and Metallization of the Quartz Veins

All evidence, both field and petrographic, points definitely to the assumption that the Cornucopia gold quartz veins have been formed by hydrothermal solutions. The source of these solutions is, however, not so evident. It is commonly assumed that vein-forming solutions are given off as final consolidation products of granitic magmas and that the position and configuration of the magma chamber is of much genetic significance.[25] At Cornucopia no such control is manifest and there is no direct evidence of magmatic origin. Some small veinlets have been formed apparently as a product of recrystallization, and it is possible that some of the larger veins derived part of their quartz by this process of metamorphic differentiation. Although the gold quartz veins are distinctly later than the metamorphic and plutonic rocks, they probably belong to the final phase of metamorphism that was characterized by decreasing temperature; hence they may be considered as having been formed by retrogressive metamorphism. During this episode, despite the decrease in temperature, shearing still continued, affording the opportunity for the upward rise of the hydrothermal solutions, which were probably alkaline, as indicated by the sericitization of the wall rocks. These solutions also caused a considerable amount of carbonatization. Development of sericite and calcite in adjacent walls and included fragments gives evidence of these occurrences.

This type of alteration is found in numerous joint cracks, which commonly have the same structural attitude as the gold quartz veins; i.e., similar strike and dip. It is especially prominent near some of the larger veins, where it produces a veritable banded effect. The bands of alteration range from a fraction of an inch to more than an inch in width parallel to the central joint plane. Where they traverse granodiorite there is reduction in grain size and a marked pinkish coloration. In the darker colored, fine-grained hornfels the alteration border is much lighter in color, commonly exhibiting a silvery appearance due to sericite. These effects are accentuated along the contacts of the larger veins and in fragments of the wall rock within the veins, but since anastomosing veinlets from the main veins traverse and even intersect the altered zones without affecting them, it is evident that this alteration preceded the quartz-forming stage.

In the field these bands of altered rock might be mistaken for injected dikes but microscopic examination of appropriate thin sections reveals a gradual replacement of the original minerals by the alteration products, which are chiefly aggregates of sericite, carbonate and quartz where the walls are granodiorite, and sericite, chlorite and carbonate where the walls are hornfels. In the altered granodiorite it is not uncommon to find one side of a feldspar crystal completely altered and the other side quite fresh. The aggregate of alteration minerals merges from one crystal to another so that only the faintest outlines of the original feldspars are discernible. The original quartz is attacked and partly replaced by quartz that has either been introduced with the hydrothermal solutions or, in part at least, has been a product of the alteration reactions. Studies of the Mother Lode veins of California have in fact suggested that most of their quartz has been derived from the wall rocks by the latter procedure.[26] In either case, however, there has been an increase in the actual amount of quartz.

The mechanism of formation of gold quartz veins has been given many interpretations, but perhaps the most common is that of a filled fracture or true fissure vein.[27] There are many gold quartz veins for which this interpretation is wholly adequate; but certain quartz veins, especially those of great lateral and vertical extent, exhibit evidence that is definitely against such an interpretation. The Cornucopia gold quartz veins are in this category. It is very difficult to reconcile the interpretation of fissure filling with such features as: the extension to depth at a relatively low angle, the multiplicity of slickensides and slipping planes, and the petrographic evidence of microbrecciation.[28] On the other hand, the presence in the vein of long, thin inclusions of the wall rock, the gradational contacts with the quartz of these inclusions and of the walls themselves, suggest metasomatic replacement processes as the most applicable mechanism. It has been maintained by some that unsupported inclusions denote the actual injection of a viscous ore magma, so that quartz veins would really be vein dikes.[29] Some of these inclusions, however, are 15 to 20 ft. long, with a maximum width of 3 in. Even where they thin down to a fraction of an inch, these elongated inclusions show no evidence of being distributed by magma flow. This fact should be sufficient to disprove the magmatic hypothesis without the petrographic evidence such as the lack of a chilled border and the presence of relics in all stages of replacement from actual rock fragments through partial silicification to complete replacement with but a mere ghost of the fragment.

The zones of alteration adjacent to the larger veins usually exhibit a coarse network of lenticular joints, which locally are followed by minute veinlets of quartz. They also, however, may contain as gouge, kaolinitic and sericitic material, surrounding cores of highly altered rock. These minor veinlets often enlarge to segregations, which increase in size and number as the vein is approached. The vein itself may contain a network of lenticular joints that have a close resemblance to the joints in the altered zones. Many of these joints within the quartz vein contain gouge, kaolinitic and sericitic material, which appears to have been derived from remnants of the initial alteration stage of vein formation.

Petrography of the Quartz Veins

One of the most noticeable microscopic characteristics of the vein quartz is a pronounced turbidity due to inclusions formed of very finely divided material and minute vacuoles. The vacuole inclusions are from 0.05 to 0.001 mm. in diameter; some with angular boundaries may be considered negative crystals; others, however, are rounded, amoebalike or tubelike in form. Vacuole inclusions locally extend from a partly replaced mineral into quartz, hence their formation may be connected with replacement processes. The concentration of the finely divided included material is commonly defined by an angular outline suggesting a ghost-relic of an original rock fragment, which is in contrast with the clearer later quartz.

Another striking microscopic feature of the Cornucopia vein is that of microbrecciation. This may be in the form of a miniature angular brecciation or it may take the form of minute shear fractures accompanied by recrystallization of the quartz to a finer grain. The usual lack of turbidity in the zones of microbrecciation may result from the filling of vacuole-inclusions by later quartz. In addition to later quartz, calcite and later ore minerals are found in zones of microbrecciation. The shearing stresses that produced the microbrecciation were particularly effective on a brittle mineral like the earlier pyrite. In some of the veins this mineral has been so crushed that it crumbles readily to very small fragments.

ORE MINERALS

Successive stages of microbrecciation permitted the continued passage of hydrothermal solutions, which cemented the fragments (Fig. 8). Under suitable physical-chemical conditions the metallic salts of these hydrothermal solutions were precipitated as later ore minerals. In general their paragenesis beginning with the earlier formed mineral is: earlier pyrite, sphalerite, galena, later pyrite, chalcopyrite, tetrahedrite, tellurides and native gold. Idiomorphism is a distinguishing feature of later pyrite. Probably the two main factors causing the precipitation of the later ore minerals were decrease in temperature consequent upon the upward rise of the solutions and the chemical effect of the earlier minerals. Petrographic studies show that these ore minerals replace the earlier quartz and the earlier pyrite. Inclusions in the quartz may have had some bearing on the precipitation. Some thin sections show what appears to be a vacuole by vacuole advance of later ore minerals through earlier quartz adjacent to fractures and zones of microbrecciation. The replacement of the earlier pyrite ranges from incipient filmlike coatings along minute fracture planes to a complete change of the earlier mineral to the later one. That such changes have taken place is proved by the crystallographic form inherited from the earlier mineral and by relics of the earlier mineral. Sections of the veins indicate that physical-chemical conditions may be quite complex, as, for instance, the dissolving of earlier quartz by later sulphide solution and at the same time the release of later quartz as a product of the reaction. This may be due to slight changes in the hydrogen-ion concentration of the solutions.[30]

Tellurides have been found in many of the Cornucopia veins and in greatest amounts in the Red Jacket and Last Chance veins.[31] Hessite, petzite and sylvanite have been identified, a most common occurrence being an intimate intergrowth of hessite and petzite with a little sylvanite and some free gold. These minerals have been the last to form and replace the earlier sulphides. They favor zones of microbrecciation and are associated with later quartz, calcite, and sometimes chlorite. In the Red Jacket mine and in the upper levels of the Last Chance mine they form bunches or pockets several inches in diameter, but of irregular distribution (Fig. 9). Although they are most characteristic of the upper portions of the veins, they have a range of over 2000 ft. below the outcrop in the Last Chance vein. Near the surface the tellurides are commonly oxidized to tellurite and the gold-bearing ones furnish a mustard colored secondary gold.

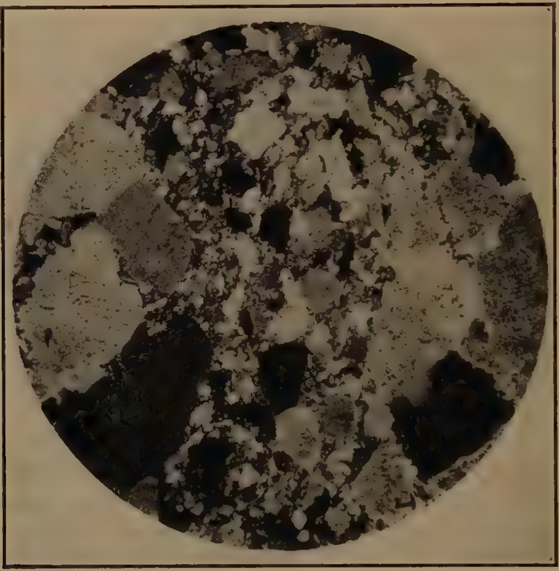

Fig. 8.—Section of Last Chance vein showing zone of microbrecciation and recementation by later quartz.

Pyrrhotite is common on the 300-ft. level below the Clark adit. In an earlier paper this was interpreted to signify higher temperature conditions of vein formation and it was expected that pyrrhotite would be one of the dominant ore minerals at depth. But when the Coulter tunnel intersected the Union vein on the 2000 level, pyrite and tetrahedite with some galena and sphalerite were found to be the dominant ore minerals, and pyrrhotite was absent. However, during subsequent development some pyrrhotite was found adjacent to a basalt dike. Moreover, this pyrrhotite had the crystallographic form of pyrite. It is assumed therefore that the pyrrhotite in this vein was formed by optalic metamorphism caused by the heat of the basalt dike. In all probability the same deduction will hold true for the upper levels of this vein, since that portion is paralleled by a basalt dike.

In general, however, the ore and gangue minerals place the Cornucopia veins in the upper mesothermal zone, although some of the upper veins such as the Red Jacket may be considered as leptothermal.[32,33] Structurally the veins occupy shear planes, which are in alignment with the tectonic features belonging to the late Mesozoic orogeny. Their characteristic microstructure is cataclastic. This microstructure is not present in some of the connecting gash veins, which are of limited extent. Such gash veins, although belonging to the same hydrothermal zone as is indicated by their mineralogy, might be termed *aclastic* in contrast to the *cataclastic* veins of great lateral and vertical extent.

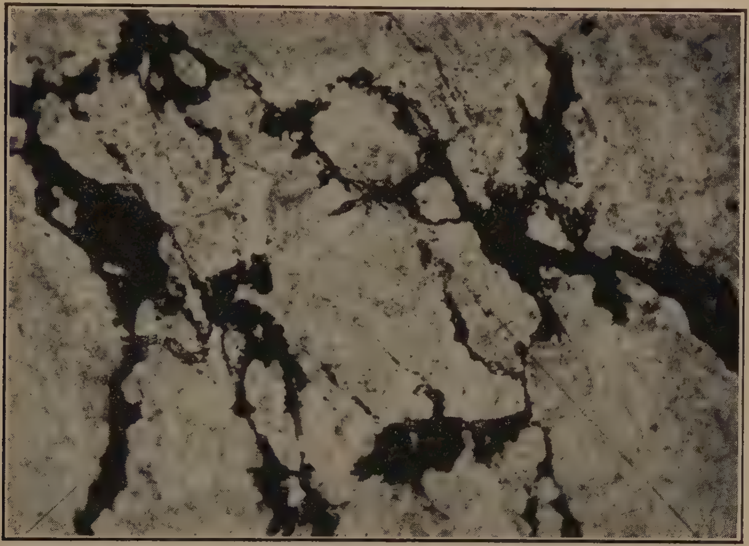

FIG. 9.—SECTION OF RED JACKET VEIN, SHOWING TELLURIDES IN ZONE OF MICROBRECCIATION.

The upper portions of the Cornucopia veins are extensively oxidized for about 500 ft. below the outcrop, while at great depths some of the more fractured portions of the veins show the effect of supergene alteration. Portions of the Last Chance vein over 2000 ft. below the outcrop are partly oxidized. Limonite is the chief supergene product, although some malachite and sooty chalcocite have been found. Since the highly fractured portions of the vein usually bear the best values, the oxidation to which they are susceptible is sometimes a reliable guide in locating ore shoots.

Summary of Formation and Metallization of Veins

1. Alteration, sericitization and carbonatization along joints or lines of fracture preceding the quartz-forming period.

2. Continued fracturing and shearing, especially along the closely spaced joints, permitting a continuous flow of solutions and a gradual replacement of the altered material by quartz, or a filling of open fractures which for the most part were probably of very small dimensions.

3. The formation of ore shoots by the recurrent fracturing and shearing of relatively large masses of brittle quartz and a continued upward penetration of hydrothermal solutions through zones of microbrecciation as well as through actual fractures and shear planes, enabling the ore-bearing solutions to come into intimate contact with the earlier formed minerals.

4. Postmineral effects include the intrusion of Tertiary basaltic dikes, a slight amount of cross faulting, and some movement along the planes of the veins as well as oxidation.

Conclusions

The recurrent fracturing of the veins is the essential characteristic that suggests their persistence to depth. This conclusion has been substantiated by the low-level Coulter tunnel, which was driven over 6000 ft. to intersect the Union Companion vein on the 2000-ft. level. At this level the cataclastic nature of the vein is even more evident than it is in the upper levels, with no diminution in average width. Hence it is expected that the other major veins of similar character will have a comparable downward extension. In contrast to the accuracy of these long-range predictions, it is very difficult to be sure of the size and shape of an irregular lenticular ore shoot. For this reason, a large number of working faces are necessary to ensure continued profitable operations.

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The San Mauricio Mining Company, José Pañganiban, Camarines Norte, P. I.

By H. L. Barr,* Member, and D. L. Gardner,† Junior Member A.I.M.E.

(New York Meeting, February 1940)

The following report covers the history of the development of the mine, present equipment, methods and costs of mining and milling. In addition, a description of the ore deposit is given with emphasis on the origin of the fractures, mode and types of ore occurrence, and mechanics of granite emplacement. An endeavor has been made to present a complete and accurate statement of the San Mauricio mine, the highest grade gold mine in the Philippine Islands.

Credit is gratefully acknowledged to the mine staff for descriptions and details regarding their particular field of work. All analyses were made by Mr. T. A. DeVore, head chemist, San Mauricio Mining Co. Messrs. Edward Wisser, J. E. Fyfe, A. F. Skerl and W. B. Meek, geologists, have contributed geologic information and ideas, for which thanks are extended.

The Executive Committee of Marsman and Co., Inc., Managers of the Company, has kindly given permission for publication. Mr. J. B. Stapler, Division Manager, Marsman and Co., has had the courtesy to read the manuscript and to give critical and helpful suggestions.

Location of Area and Scope of Work

San Mauricio Mining Co. controls a group of 113 claims that lie immediately north of the town of José Pañganiban (formerly Mambulao), Camarines Norte, Luzon, P. I. (Fig. 1). Exploration work commenced in the spring of 1934; active development began in the fall of that year and has continued to the present date. Mill construction was begun Oct. 15, 1935, and production started March 10, 1936. Total production to June 1, 1939, is ₱10,499,105.15 ($5,249,552.57).‡

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† Geologist and Chief Engineer, San Mauricio Mining Co.; Geologist, Southern Division, Marsman and Co., Inc.

‡ Values quoted are in pesos with gold at ₱70.00 per ounce, unless otherwise stated. Exchange to U. S. Currency is 2:1.

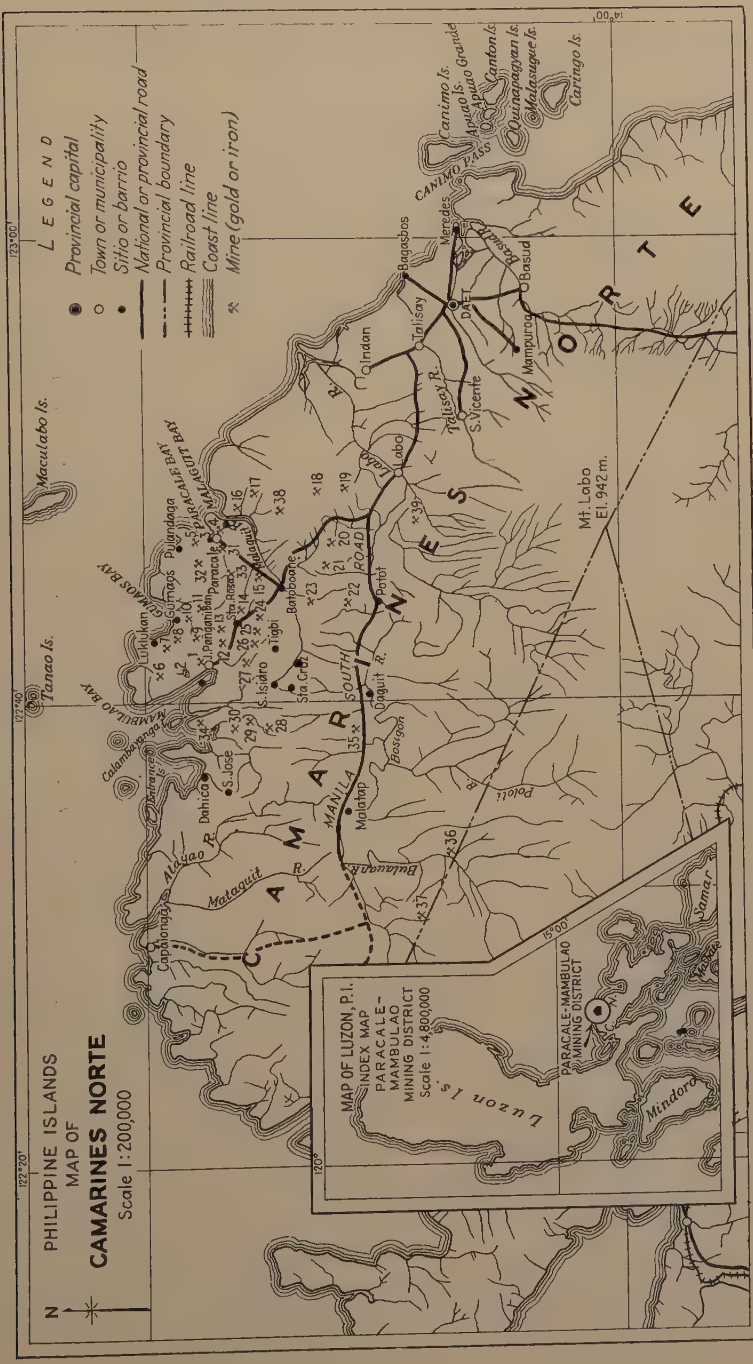

FIG. 1.—For descriptive legend see opposite page.

Mill capacity was increased during June 1939 to 450 tons per day. Production will range from ₱550,000 ($275,000) to ₱600,000 ($300,000) per month.

History of Property

From fragments of pottery in camp sites adjacent to the present mine, it is evident that the property was worked in higher horizons spasmodically over a long period of time before the eighteenth and nineteenth century work of the Spaniards. The following statement by Dr. H. Otley Beyer, anthropologist, University of the Philippines, concisely summarizes all the knowledge of the early activity in the Paracale-Mambulao district.

> Two periods of ancient mining seem to be indicated by the pre-Spanish remains found in the Paracale district. First, certain of the ancient gold beads and celadon specimens found seem to date from the 12th to early 14th centuries, A. D. (late Sung and Yuan), and probably indicate a pre-Madjapahit period of activity in the district. Probably only placer mining was then current. Second, most of the pre-Spanish ceramic wares and other remains found date from the 15th (or possibly the late 14th) and 16th centuries, A. D., and seem to cover chiefly the period when Javanese miners from Madjapahit were working in the district, and introduced the Indian quicklime method of lode mining. The known period of Javanese domination of Southern Luzon is from about 1350 to 1480 A. D. It was doubtless during this time, however, that the Ming Chinese traders became most active in "Tung Liu-Sin" (Eastern Luzon), and began to speak of the region south of "Pu-li-lu" (present Polillo) as "the land of gold." The exact reference in a Chinese book of 1368 is: " To the south of this traders did no mining themselves but merely bought up the product of the gold washings and diggings of the people there, in exchange for ceramics, textiles, jewelry, and other manufactured articles." It is probable that this Chinese contact continued

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FIG. 1.—CAMARINES NORTE MINING DISTRICT, PHILIPPINE ISLANDS.

Mining Companies

1. San Mauricio Mining Co.
2. Philippine Smelting Co.
3. Coco Grove, Inc.
4. United Paracale Mining Co.
5. Tinga Gold Mining Co.
6. Insular Gold Mining Co.
7. Paracale Daguit Gold Mines, Inc.
8. Santa Barbara Mining Co.
9. Mambulao Cons. Mining Co.
10. Gumaos Goldfields, Inc.
11. Paracale Gumaos Cons. Min. Co.
12. Mother Lode Mining Co.
13. Santa Rosa Mining Co.
14. Mambulao Gold Mining Co.
15. Paracale Daguit Gold Mines, Inc.
16. Malaguit Mining Co.
17. Paracale De Oro Mining Syndicate
18. Labo Mother Lode
19. Labo-Sta. Ana-San Joaquin United Mines, Inc.
20. Paracale Mining Development Co.
21. Santo Niño Mining Co.
22. Quartz Hill Mining Co. (Potot group).
23. Batobalani Mining Co.
24. Equitable Exploration Co.
25. Universal Exploration and Min. Co.
26. Paracale National Gold Mining Co.
27. Consolidated Mines, Inc.
28. Tigbi Exploration Co.
29. Homestake Gold Mining Co.
30. Paracale Goldfields, Assn.
31. North Camarines Gold Mining Co.
32. Paracale Mining Development Co.
33. Paracale Gold Mining Co.
34. Philippine Iron Mines.
35. Mayon Mining Co.
36. Northern Mining and Dev. Co (Tuba project).
37. Suterios group.
38. Paracale Iron Mines.
39. Mineral Resources, Inc.

uninterruptedly down until the Spanish occupation, long after the original Javanese miners had left the district.[1]

District records show annual production of 350,000 pesos or more during two centuries of Spanish activity. The total production must have been greater, for the Spanish Crown demanded a royalty of 20 per cent, which naturally was evaded if possible.

The Spanish exploration of the district began in 1572. The exact time of the initiation of mining by Spaniards at San Mauricio is not known but the greatest recorded period of activity in Spanish times was in 1609, when 700,000 pesos was reported from the district.[2]

Active lode mining of the property is known to have occurred during the late eighteenth and early nineteenth centuries, which probably was the time at which the present San Mauricio (1000 stope), Tacoma Nos. 1, 2, 3, Santa Ana, and other veins were exploited.

The Tacoma No. 3 area was known at that time as the Doña Punay, presumably being the concession of the lady that sent the Queen of Spain a gift of hen and chicks made of gold, when asking for a fort with soldiers as a protection against raiding Moros. Legend or not, the typical small fort was built in the seventeenth century and still stands on a knoll above José Pañganiban.

The Tacoma No. 3 vein was mined in certain sections to a point 30 ft. below the present 200-ft. level, a vertical distance of 320 ft. below the surface. Entrance appears to have been obtained by means of a surface adit about 8 ft. below the present Tacoma ventilation adit. Underhand stoping was used and the lower portions were worked only in the dry season, when the water could be bailed. Shafts were sunk on adjoining veins, which probably were separate properties. One was sunk near the 1000-ft. stope and a second north of the present Tacoma shaft.

Production records for the mine are fragmentary, but considerable gold from fabulously rich ore was obtained. What was missed and left as scabs, footwall stringers, pockets and fill was considerable, although the *ancianos* were good miners and timbermen. Drift timber in the old workings, of round, cut and fitted posts, caps, and lagging, is a tight, firm job put together without nails.

The mine must have been shut down by water troubles before 1845, for in that year Don Isidro Sainz de Baranda formed the Ancla de Oro Company to drive a sea-level drainage adit. Funds were raised and the project was started, to be abandoned after 50 meters, because of very bad ground.

Although the Ancla de Oro adit was opened in 1918 and reopened in 1935, maintenance costs were excessive. Successful drainage of the mine was not obtained until the Reed adit was complete in 1938 by the present company in better ground farther to the west.

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[1] H. O. Beyer: Personal communication, May 25, 1939.

[2] H. L. Barr: *Marsman Magazine* (Nov. 1937) **2**, No. 5.

After 1845, work was intermittently carried on until the insurrection in 1899. In October 1902, the group was examined by W. B. Vanderlip, but although his report was very favorable work was not resumed.

An attempt to open the mine was next made in 1909–1910. A 10-stamp mill was erected and some development work done. A shaft was sunk to the 200-ft. level and drifts were run on the vein. Ore was developed and some was stoped, but the mill was shut down at the end of six months because of the complex nature of the ore. The gold was associated with copper, lead and zinc, and only 40 per cent recovery was made by plate amalgamation.

In 1918 the Ancla de Oro drainage adit was completed and the mine was unwatered above sea level. The sampling results were not encouraging, considering the high cost of materials during the "after war boom" and work was abandoned.

The claims were held by Messrs. F. B. Ingersoll, E. B. Heise and associates until 1933, when the property was examined by Mr. J. O. Enberg, of Marsman and Company, Inc., who acquired the property and formed the San Mauricio Mining Company.

Topography, Climate, Water and Vegetation

The claim group covers most of the Mambulao Peninsula (Fig. 2), which extends as a thumblike projection northward into the Pacific. The present producing areas are in the southern section of the property near the base of the thumb. The mine plant is on a ridge above Mambulao Bay at an elevation of 270 ft. The highest point on the group is May Cruz at an elevation of 1200 ft. Elevations are higher along the northern contact but break from there in irregular slopes in all directions to sea level. Steep, youthful canyons leading to higher flats and alluviated valleys indicate a recent uplift of the area.

The climate is tropical. In 1938 the rainfall was 168 in., most of which fell during the winter months, when torrential rainfall due to passing typhoons is to be expected. The heaviest rainfall recorded was 6 in. in 30 min. during a thunderstorm in December 1938. Day temperatures during the dry season range from 80° to 95°F. Humidity varies from 85 to 65 per cent.

Operating conditions are good. The climate is healthful and the district is comparatively free from malaria and other tropical diseases.

Ample water is furnished during the wet season from small dams on Doña Punay and Fabrica Creeks. During the dry season of May to September, water is scarce. As the mine water is too acid for mill work (pH equals 5.5, average), the mill is run during these months on sea water pumped from Mambulao Bay.

The area is covered with tropical vegetation and supports a moderately thick stand of tropical hardwoods, some of which reach large diameters.

SUMMARY OF REGIONAL GEOLOGY*

Sediments, volcanics, and what is termed the "metamorphic complex" are intruded by plutonic bodies, the most important of which, from an economic standpoint, is the Paracale-Mambulao granitic stock, which has a known length of 12 km. and a maximum breadth of 4 km. on a sea-level projection. The long axis of the stock trends N. 70°W. parallel to the rift lines along the coast and to the faults along the southern contact. Most of the economic gold ores developed to date are localized in the granite. Prominent features of the intrusive are western and eastern upswells with cross joints, which, when favorably oriented, were reopened for mineralization. Minor domes and protuberances of

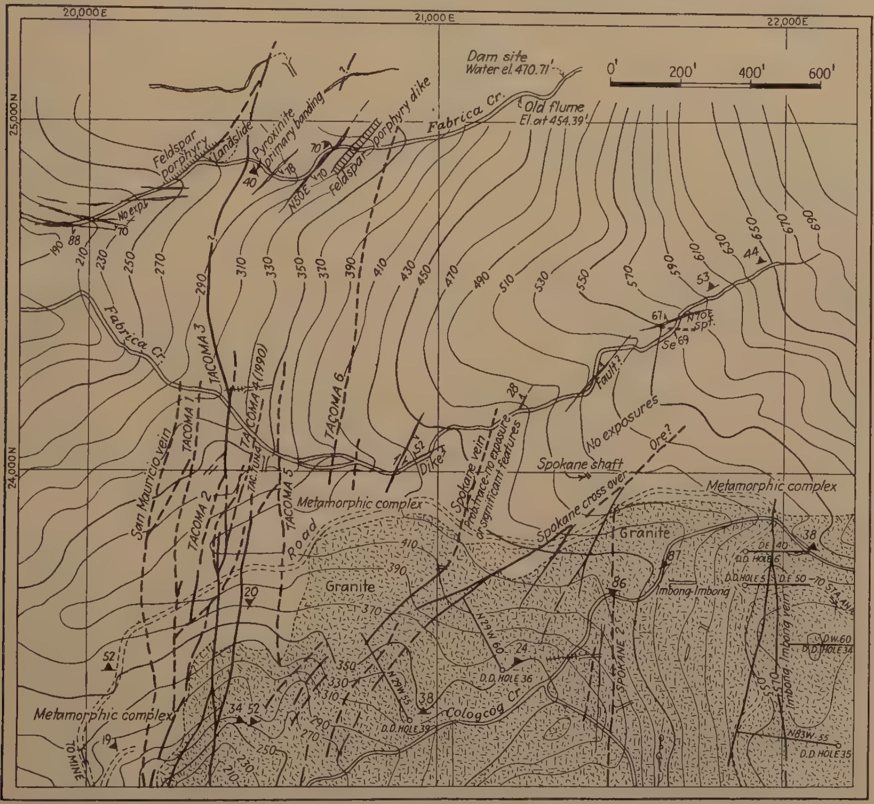

FIG. 2.—SURFACE GEOLOGY, SHOWING TOPOGRAPHY TACOMA AND SPOKANE AREAS, MAMBULAO, CAMARINES NORTE, PHILIPPINE ISLANDS.

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* Further detail is presented in a report to Marsman and Co.—Geology of Paracale-Mambulao Mining District, by Dion L. Gardner. Permission for publication of the essential outlines of this report has been granted.

granite occur along the crest and flanks of the main mass, each with a dominant joint orientation of its own; septa-like inclusions of schist within and along the contact serve to localize faults and fault veins developed during regional stress at the time of mineralization.

SUMMARY OF GEOLOGY OF SAN MAURICIO

San Mauricio is a gold lode deposit at the western end of the Paracale-Mambulao stock. Gold ore occurs in cross joints, which developed during the intrusion of the granite. Kersantite and malchite dikes occur and ore is found in the cross joints in definite shoots. Three major spaced vein systems trend N.5°W. to N.15°E. and dip east. The following are from west to east: (1) San Mauricio and Tacoma, (2) Santa Monica and (3) Santa Ana. Parallel intermediate veins are known at spaced intervals between them. Metallic minerals are pyrite (two types), sphalerite (three types), galena (two types), chalcopyrite, tetrahedrite, tennantite, stephanite, molybdenite, and an unknown mineral (*X* mineral). Gangue minerals are quartz, manganocalcite, siderite and chlorite. Gold occurs free and in intimate association with galena, sphalerite, tetrahedrite, tennantite, molybdenite and *X* mineral, localized in high-grade ore shoots. Locally high values occur in pyrite-chalcopyrite ore. Ore is divisible into the following types with gradations between them: Tacoma ore; Santa Ana ore; Brooklyn ore; pyrite-chalcopyrite ore; and "contact ore."

The granite was emplaced and the fracture pattern developed under mild regional compressive stress acting from the northeast; this stress and incident fault movement continued during mineralization, which was the latest event in the history with the exception of erosion and a slight recent uplift.

GENERAL GEOLOGY

For practical purposes only two mapping units have been used; that is, (1) metamorphic complex and (2) granitic rocks. Both may be subdivided as noted on the underground sheets.

Metamorphic Complex

The unit occurs around the margins of the stock extending to the ocean from the northern contact. The southern marginal strip is narrow but continuous, schists and serpentine being everywhere in contact with the main granite mass. Dikes and tabular bodies of granitic rocks are found generally within the unit but are especially abundant to the north. Serpentine, serpentinite, talc schists, chlorite schists and amphibole rocks are present. The exact interrelationships are not yet known. A marked contact zone is distinguishable along the western and southern borders.

Serpentine.—Serpentine, derived in large part from peridotite, occurs in the metamorphic complex as large bodies and irregular masses. The original rock type is rarely discernible but a few specimens have been found that contain residual olivine and chromite nodules and segregations.

The rock is dull green in color and massive in character, with abundant slippage along internal joint fractures. In a specimen from Luklukan Point, olivine occurs as irregular, corroded, brecciated fragments, altering to a serpentine matrix that is cut by stringers of dull green serpentine. Chromite nodules occur. The rock is probably a peridotite, although dunite would alter in the same manner.

Serpentinite.—Serpentinite is very common in the complex and is distinguished from serpentine with difficulty, since it sometimes alters to the latter. It occurs as large bodies and irregular masses composing approximately 60 per cent of the complex. The origin of the rock is not known; possibly it is derived from a basic volcanic series.

The rock is dull green in color, altering and weathering to duller hues of green. Fresh specimens are massive and jointed; on weathering, parallel joints simulating bedding structures are discernible.

The rock consists almost entirely of antigorite with a few rare basic plagioclase grains. The antigorite fibers are of variable sizes; the average size of a bundle aggregate is about 1 millimeter.

Talc Schists, Diabasic Talc Schists and Chlorite Schists.—In the immediate vicinity of vein zones and along the southern contact, metamorphism and hydrothermal alteration have combined to produce talc schists and diabasic talc schists. Along the southern contact these rocks are believed to be the metamorphosed equivalents of interbedded diabases of the Universal Shale series, which occurs south of the major faulting along the southern border of the stock. Diabasic talc schists within the metamorphic complex along vein zones are due to alteration during mineralization. Schistosity in most instances is caused directly by invading granite.

Amphibole Rocks.—Amphibole-rich rocks occur in the contact zone at San Mauricio, along the south, west, and part of the north side of the intrusive. They are found as definite bands from 1 to 15 ft. thick with a fine-grained, occasionally porphyritic texture suggesting a chilled phase of the granite. In places distinct gradations from amphibole rocks to slates with well developed cleavage and folding are observed but between hornblende rocks and chilled granite no such gradation is observed and sharp contacts are characteristic. The origin of the hornblende rocks is not clear. They are thought to be inclusions of intensely altered sediments, penetrated by a border phase of the granite with no admixing of the two units. Thickness varies from 100 to 380 feet.

Medium to large hornblende grains (70 per cent) are enclosed in a mesh of anhedral feldspar (30 per cent). Hornblende grains are oriented parallel to the flow banding in the intervening chilled granite and in the main border phase of the granite.

Plutonic Complex

More work has been done on the granite and granite differentiates than upon the metamorphic complex, since it was expected that a close study of the granite and mechanics of its intrusion might permit a resolution of the stresses that formed the mineralized fractures.

Many minor variants of the granite are found with a large number of definite differentiation products, which occur as dikes and sills. The vein fractures developed shortly after the solidification of the stock and as a direct result of emplacement. Major ore shoots developed on favorably oriented fractures during a period of compressive stress from the northeast. Cross joints in the granite swells relieved the horizontal shearing stress and were opened for mineralization.

PARACALE-MAMBULAO GRANITE

The granite and related rocks of the western end of the stock can be divided into the following types, presumably a differentiation series:

1. Central core
2. Marginal facies
3. Aplite phases
4. Dike rocks
    - *a.* Granite porphyry and acid granite
    - *b.* Pegmatite and aplite
    - *c.* Basic dikes
        - (1) Parallel to flow banding
        - (2) Perpendicular to flow banding following cross joints

Paracale-Mambulao Granite

Many minor variations occur in the composition but all facies of the rock are characterized by the presence of biotite, albite, and variable amounts of quartz. The proportion of quartz, the amount of biotite, the rate of cooling, and the presence or absence of flowage, are the dominant factors in the localization of the variations. No hornblende or pyroxene have been found.

Central Core.—The central core of the intrusive is massive in appearance. It consists of feldspar, quartz and biotite. Flow banding is not pronounced, but when present it trends N. 30°–40°W. and dips steeply. The rock appears to have solidified over a longer time than the marginal phases.

The rock is uneven granular granite composed of euhedral and anhedral feldspar, quartz and biotite.

Marginal Facies.—Changes in the mineral composition of the central core toward its margins are not important. In the marginal areas, banding is well developed because of parallel orientation of biotite crystals.

Santa Ana Variant

A distinct rock type is in the Santa Ana area in the vicinity of the shaft and on both walls of the vein. This type is believed to be a late surge of the intrusion. Flow banding is developed locally and the rock encloses aplite phases, and is cut by narrow aplite dikes and thin pegmatite dikes.

The rock is distinctly uneven granular granite. Euhedral and subhedral albite and biotite occur with an abundance (25 per cent) of anhedral quartz.

Aplite Phases.—Locally, irregular masses of aplite intrude the granite. These are especially prominent east of Santa Ana along the northern contact between Santa Ana and Paracale Bay.

Dike Rocks

Dike rocks include granite porphyry, acid granites, and granite aplite. These rocks are granite differentiates that occur as dikes and sill-like bodies in the metamorphic complex.

Granite porphyry is well exposed at Longos, Kalaw and elsewhere in the district. It is not present at San Mauricio, where only occasional sill-like layers of porphyritic granite 1 or 2 ft. thick have penetrated the flow banding. The porphyritic rock, which contains prominent feldspar phenocrysts, is strongly banded and darker than the surrounding granite.

Acid granite is the common granitic rock in the metamorphic area on the peninsula. It appears in the form of irregular and faulted dikes and sills, which range from 2 to 10 ft. in thickness. Most of the dikes strike northwest and dip south. The light colored rock consists of a fine-grained, even granular granitoid intergrowth of quartz and feldspar.

Granite aplite occurs as northwest-trending dikes in serpentine.

Aplite and Pegmatite Dikes

Dike rocks of this character occur in a few instances at Santa Ana, but have not been observed elsewhere on San Mauricio ground.

Aplite Dikes.—These dikes strike northwest parallel to the contact and flow banding, but dip at a lesser angle to the south. Their thickness varies from 4 to 12 in. The dikes are discontinuous and are earlier than pegmatites. The rock is light colored and fine-grained with a sugary granitoid texture. Anhedral quartz and feldspar are present in nearly equal amounts.

Pegmatite Dikes.—These are very rare but are found as thin, discontinuous dikes, which cut the Santa Ana granite and the aplites. The rock is uneven granular with abundant large soda-orthoclase crystals and quartz. Grain size is from 1 to 2 cm. None is of a giant grain size. Small, dark red, anhedral garnet grains are present, but no other accessory minerals occur.

Basic Dikes

Basic dikes possess two modes of occurrence, which are: (1) parallel to the flow banding, and (2) intruding north-trending cross joints.

Dikes parallel to the banding are seldom present in the Tacoma area; they occur as thin (4 to 16-in.) dikes, which strike northeast and dip west. They are offset by the cross joints.

Basic dikes fill cross joints that are developed within major fractures: Thus, within the San Mauricio-Tacoma, Santa Monica and Santa Ana veins these dikes are up to 10 ft. thick. They are very irregular and do not persist in the ore shoots.

Kersantites (Biotite Feldspar Lamprophyre)

This rock is a dominant dike type, but minor variations are found in different veins The width, continuity, and intensity of alteration also vary along the strike and dip. The rock is fine to medium-grained, uneven granular, dark gray to black in color, consisting of basic plagioclase (labradorite) with biotite and hornblende grains. Fine-grained facies occur associated with narrow dike stringers and as chilled margins. Thicker dikes are medium granular with a felted net of biotite plates and interstitial plagioclase and minor quartz. Quartz may or may not be present, but commonly occurs in small amounts. Magnetite and titanite are present. Calcite and chlorite are dominant secondary minerals. At some places the dikes are intensely calcified and contain silica stringers; at others they are hydrothermally leached and pyritized.

Malchite Dikes

Malchite penetrates part of the Santa Ana fracture, as a footwall dike about 4 ft. wide. At intervals it diverges from the vein structure. It is discontinuous along any one fracture, but persistent throughout the strike length of the vein.

The rock is dark in color with a granitoid texture consisting of feldspar (35 per cent) altered to calcite, hornblende (25 per cent) and augite (10 per cent). Accessory minerals are magnetite and apatite.

Alteration

The rock types mentioned, in the vicinity of vein zones, exhibit four phases of alteration, all of which are not developed in any one locality.

Gneissoid Structures

Flow banding developed in the granite probably during its intrusion. It is variable in degree of perfection and represents flow bulges, sinks and irregularities of flow of the granite magma; it also reflects the trend and irregularities of the adjacent contact surface.

Flow banding is regular and even along the southern contact. To the west the termination of the upswell produced two west-trending secondary ridges. Along the northern contact in the Tacoma area, banding is rather even and similar with a trend of N. 30°E. and a dip to the north ranging from 29° at a higher to 21° at lower elevations. In the Imbong-Imbong area steep northeast bands are developed on the flank of a large granite swell. Mineralization is believed to occur in the major fracturing effected to the north. Areal relationships indicate that these concealed fractures will be favorable for ore. Early in 1938 exploration was directed toward the area from the 200-ft. level by means of the 1500-ft. crosscut. Recently good ore has been found on the margins of the area, and continued exploration is expected to disclose important ore bodies.

Regular and even flow banding occurs across the exposed northern portion of the stock from Imbong-Imbong east to and beyond Santa Monica. In the Santa Ana area flow banding trends northwest and dips south, and the granite appears to have advanced from that direction in the form of overriding tongues and sills.

Since the banding in the core of the western upswell trends N. 30°-40°W. and dips steeply, it appears that the central part of the mass rose during regional compression, which acted from the northeast. Locally the core seems to incline slightly to the north. The flowage around the south, west, and part of the north side may be drag flowage produced by the rise of this central core to higher elevations.

Cross Joints (Fractures)

Flow lines are not visible in the granite core nor in the marginal phases. From their trend, characteristics and position, joints are assumed to be cross failures at right angles to the direction of flow. These trend northeast and dip east. The fan of cross joints across the upswell is imperfect.

Three major spaced cross-joint vein systems occur in the western end of the stock near San Mauricio. These are: (1) San Mauricio-Tacoma, (2) Santa Monica, and (3) Santa Ana. Spokane, Spokane No. 2, Imbong-Imbong, Tacoma 5, 6, 7, 8, Turayog No. 1 and 2, all of which are termed intermediate veins.

The fracture system conforms to a definite pattern throughout the entire area and is reproduced on a small scale on individual vein systems. The N. 5°W. to N. 15°E. cross joints are dominant, while the N. 45°–50°E. cross joints and "crossovers" are secondary features resulting from local irregularities of flow or torsional stress existing between two cross joints subjected to horizontal shear. Northwest faults are known to occur along the southern contact and are believed to exist north beneath the ocean.

San Mauricio-Tacoma No. 3 *Vein System.*—This system includes a series of cross joints at the western end of the granite stock. Mapping of the system shows that it extends for a strike length of 4000 ft. with the north limits not yet disclosed. The two major parallel veins are about 150 ft. apart. "Crossovers" connect these. Ore occurs in definite shoots in the main veins and crossovers. On the 200-ft. level of the San Mauricio vein system there is an almost continuous lateral extent of ore for over 2000 ft. Ore occurs at the intersection of "crossovers" with the main veins where two important high-grade shoots have been found; others are believed to exist. Low-grade ore borders the rich shoots. High assays are characteristic of all the ore zones, but some dilution is experienced in mining.

Ore shoots are localized by structural features. The 1000 stope area on the San Mauricio vein, which was an extremely high-grade spot about 250 ft. in diameter, which contained leached ore of the Tacoma type, was controlled in part by a vein intersection with Tacoma No. 1 and in part by synclinal structures below a major anticlinal axis of group 1.[3] Some zinc and manganocalcite was leached but gold did not migrate appreciably. Other localities on the San Mauricio vein in which repetition of this type of structure is expected are considered favorable prospects for future exploration.

Tacoma No. 3 *Vein.*—The Tacoma No. 3 vein is a second important structure of the San Mauricio system. The lodes have been traced on the surface for more than 4000 ft. One important blind ore shoot has been found, which is partly developed on the 200, 300, 400 and 500-ft. levels. A smaller ore shoot, called the "fault ore body," is very high in grade. The Tacoma No. 3 ore shoot is believed to be terminated on the south by numerous diverging splits. To the north and upward, the shoot is beneath the flat, north-dipping contact. Some large bodies of "contact ore" occur and continuations of the Tacoma No. 3 shoot may be traced downward along the contact.

Fig. 3 is a plan and section of the Tacoma No. 3 ore shoot as it is known at present. Noteworthy features are: (1) localization of ore in the granite beneath the overlying contact, (2) spacing of the hanging-wall and footwall splits, (3) persistence of some splits within the explored area, (4) dying out of others, and (5) a tendency for high-grade ore to be at split intersections.

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[3] D. L. Gardner: 94 Gold Structure Contour Map. Private report to San Mauricio Mining Co., Dec. 28, 1938.

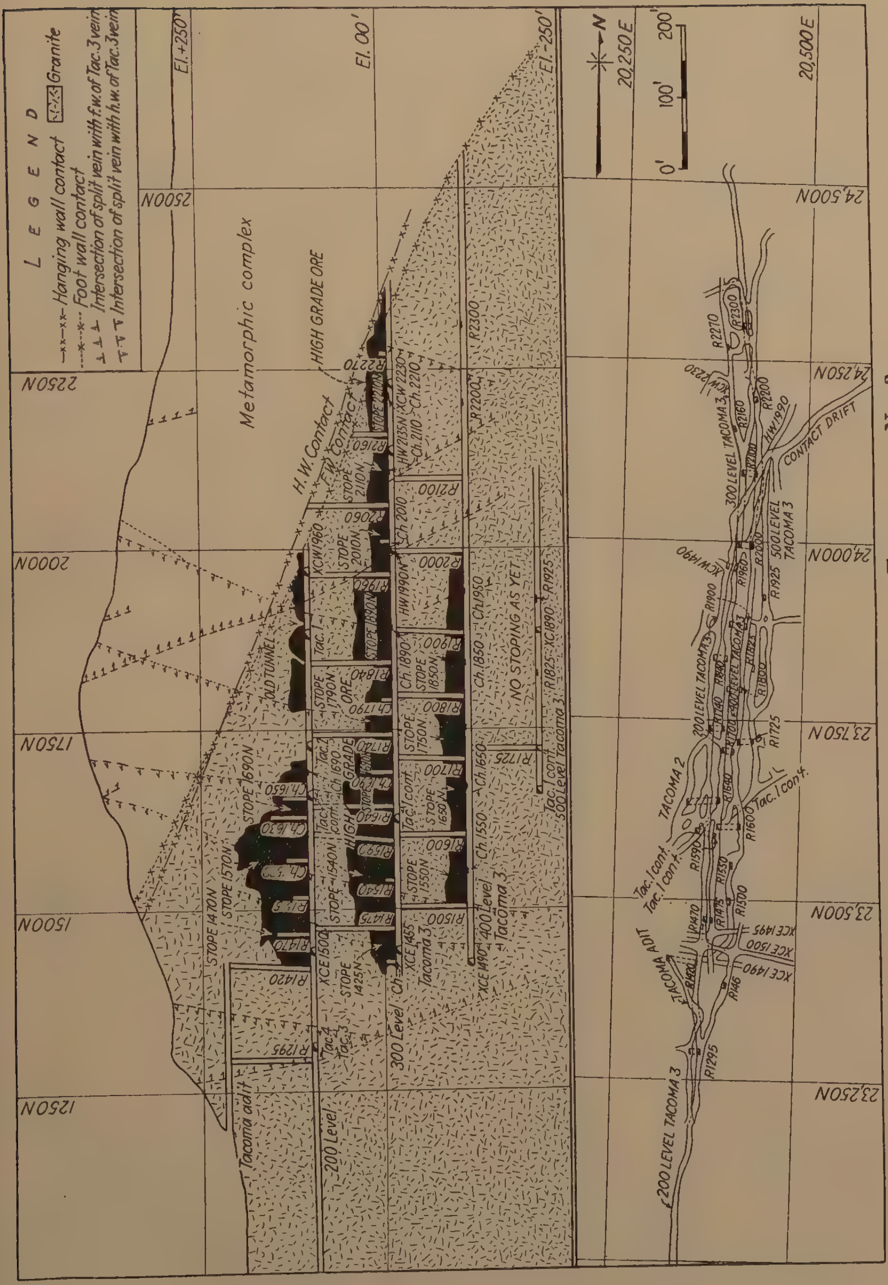

FIG. 3.—PLAN AND SECTION OF TACOMA VEIN NO. 3.

Santa Ana Vein System.—This vein is one of the strongest in the area. It trends N.8° to 15°E. and dips east at angles ranging from 55° to 80°. Width varies between ½ and 10 ft., the average being about 4½ ft. Below flat-lying surfaces local bulges attain widths of 20 ft. A malchite dike occurs discontinuously along the vein. Ore of the Santa Ana type has been disclosed on the 300-ft. and 425-ft. levels and in smaller amounts on the 150-ft. level. Further detail is shown in Fig. 4. The hanging wall of the structure is intensely fractured for a distance of 2000 ft. These intersecting breaks are of two types: (1) south-dipping joints parallel to flow bands and (2) cross joints.

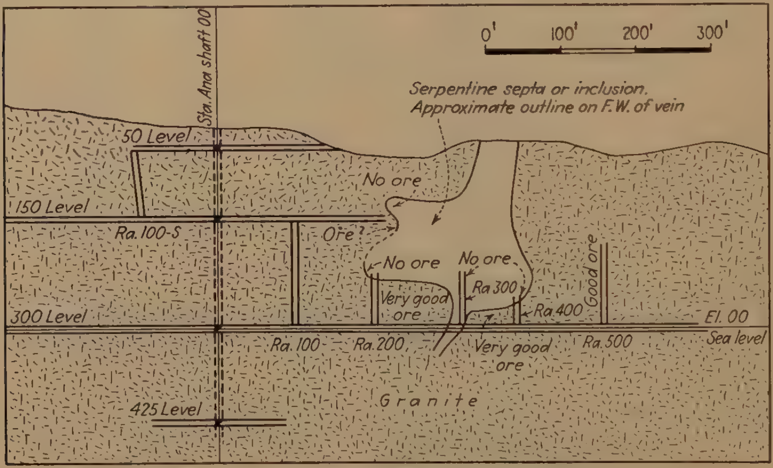

FIG. 4.—SANTA ANA FOOTWALL OF HANGING-WALL SPLIT.

Sketch showing relationship of ore on Santa Ana vein, 300-ft. level, to serpentine septa (inclusion) on footwall of hanging-wall split. Very good ore, wide veins, strong quartz, and sulphides with good values are localized beneath flat upper contacts of granite serpentine where the vein intersects the inclusion. In serpentine, the veins thin to narrow gouge seams with minor quartz, scant to no sulphides, and low to no gold content. There is slight to no surface indications of these important ore bodies at the outcrop in serpentine areas.

Santa Monica Vein.—This strong fracture in granite is similar to the Santa Ana vein in many respects. The zone has been traced on the surface for 7200 ft. along a N.8°E. trend. The dip is east. Only spotty and low-grade ore has been found. The fracture pattern in the easterly portion resembles that noted in the hanging wall of the Santa Ana vein. Exploration of all the fractures between Spokane and Santa Ana structures may lead to important ore discoveries north of the present development on the Santa Monica vein and other intermediate veins.

Ore Types

Ore is subdivided into several types but productive shoots usually contain more than one type.

Tacoma and 1000-stope Ore of San Mauricio.—The ore, which is rich in gold, contains dominant sphalerite and galena with sparse manganocalcite and minor quartz, pyrite and chalcopyrite. The gold is free and in intimate association with sphalerite and galena. It occurs in definite shoots.

Santa Ana Ore.—Santa Ana ore is also a high-grade type, characterized by much quartz, brown and black sphalerite, pyrite and chalcopyrite. Gold is free and closely associated with sphalerite and galena. The ore occurs in definite shoots.

Brooklyn Type.—The Brooklyn ore is low-grade and characterized by large open vugs coated with chalcopyrite and pyrite.

Pyrite-chalcopyrite.—The high-grade pyrite-chalcopyrite ore is associated with much quartz. Gold associated with pyrite occurs free and in the pyrite and chalcopyrite.

"Contact Ore."—Contact ore is characterized by the presence of green quartz but otherwise is similar to common vein material. The green quartz occurs with stringers of later quartz, sulphides, and free gold. The "contact ore" is of good grade, sometimes massive, but more often rudely banded.

Ore Textures and Structures in Cross Joints

The vein filling in cross joints is banded parallel to the walls, which are fairly continuous and straight. The mineral assemblage, which includes quartz, fractured wall rock and dike material, fills comparatively narrow openings. Accretion is persistently present in the more extensive shoots. Lensing and pinching of the vein is characteristic, although the structure is continuous and regular. Fault gouge is unimportant, but generally present.

Shoots are localized by structural controls in which deviations in strike and dip, vein intersections, and contacts, determine the extent of the opening. Some ore occurs in seams and stringers in sheeted zones, in disseminations and stringers in silicified granite.

Ore Genesis

The structural relationships and mineral assemblage suggest vein formation by solutions probably derived from a differentiate of the granite.

Conditions of Formation.—The important hypogene minerals are galena, sphalerite, chalcopyrite and pyrite with dominant quartz and very minor carbonate gangue associations. These are characteristic of mineralization in the outer mesothermal and lower epithermal zones. Only one period of mineral introduction is recognized, although the variations in mineral assemblage at different localities indicates the existence of more than one source.

Process of Vein Formation.—In the veins, abundant evidence indicates repeated minor fracturing and partial replacement of the earlier quartz, sulphides and gold. Both accretion and replacement have been active.

Localization of Ore Shoots.—Ore is localized in shoots along the veins. These shoots have resulted from conditions of internal structure. As stated before, the ore in the 1000 stope on the San Mauricio vein is related to intersecting breaks and to synclinal structures on the vein surface below a major anticlinal trend. The Tacoma ore shoot is controlled by the overlying impervious cover (the contact surface) and terminates to the south by a divergence in strike where the structure splits. High-grade trends in the ore shoot are controlled by footwall and hanging-wall splits, of which footwall splits exert the greatest influence. Ore follows up along the vein, turns over, and lies along the contact, some large bodies of "contact ore" being localized in this manner. Good high-grade ore occurs in hanging-wall splits and in fracture zones in silicified granite in the walls of the main veins. Part of the Santa Ana ore is localized on the vein in a favorable strike and dip zone below a flat-lying contact surface, as is illustrated in Fig. 5.

Minerals Present

The mineralogy is comparatively simple. The following primary metallic minerals have been identified:

1. Pyrite (two types) common.
2. Sphalerite (three types) common.
3. Galena (two types) common.
4. Chalcopyrite—common.
5. Stephanite—very rare.
6. *X* mineral. Rare, locally common. A new mineral, with probable composition As, Fe, Zn(CoN)(Sb)O + S.
7. Tetrahedrite—rare.
8. Tennantite—very rare.
9. Gold with silver.
10. Molybdenite.

Nonmetallic minerals found are:

1. Quartz—three generations and many types. Common
2. Chlorite—common in some ore.
3. Siderite—rare. Limited to one occurrence.
4. Manganocalcite—rare. Locally common, never dominant
5. Dickite—rare. Two or three localities.

Mineral descriptions and occurrences are omitted for the sake of brevity.

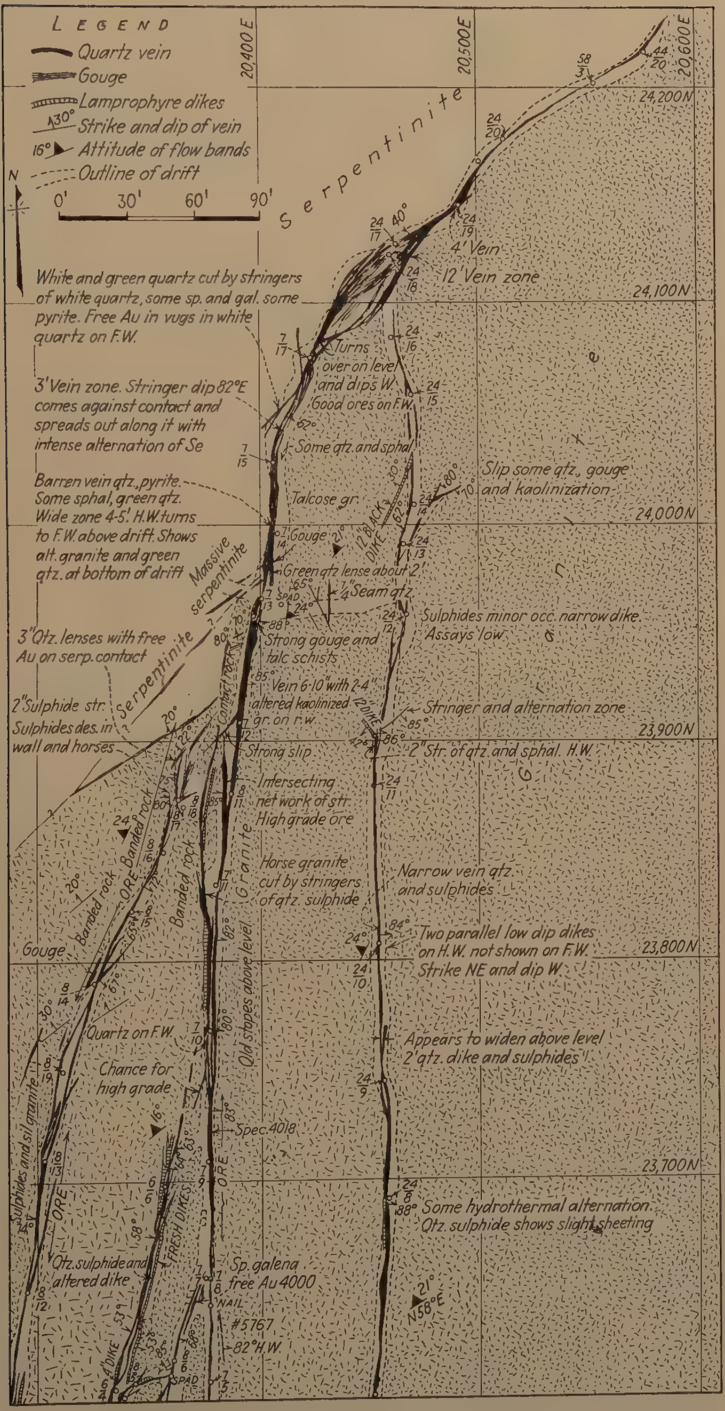
LEGEND
Quartz vein
Gouge
Lamprophyre dikes
30° Strike and dip of vein
16° Attitude of flow bands
Outline of drift
N
0' 30' 60' 90'
20,400 E
20,500 E
20,600 E
24,200 N
24,100 N
24,000 N
23,900 N
23,800 N
23,700 N
Serpentinite
Granite
4' Vein
12' Vein zone
White and green quartz cut by stringers of white quartz, some sp. and gal. some pyrite. Free Au in vugs in white quartz on F.W.
Turns over on level and dips W. Good ores on F.W.
3' Vein zone. Stringer dip 82°E comes against contact and spreads out along it with intense alternation of Se
Some qtz. and sphal.
Slip some qtz., gouge and kaolinization
Barren vein qtz., pyrite. Some sphal, green qtz. Wide zone 4-5'. H.W. turns to F.W. above drift. Shows alt. granite and green qtz. at bottom of drift
Talcose gr.
Gouge
12' BLACK DIKE
Massive serpentinite
Green qtz lense about 2'
1/4" Seam qtz.
Sulphides minor occ. narrow dike. Assays low
3" Qtz. lenses with free Au on serp. contact
Strong gouge and talc schists
Vein 6-10" with 2-4" altered kaolinized gr. on r.w.
Serpentinite
Contact rock
2" Sulphide str. Sulphides des. in wall and horses
Stringer and alternation zone
2" Str. of qtz. and sphal. H.W.
Strong slip
Intersecting net work of str. High grade ore
Banded rock
ORE
Banded rock
Horse granite cut by stringers of qtz. sulphide
Narrow vein qtz. and sulphides
Two parallel low dip dikes on H.W. not shown on F.W. Strike NE and dip W.
Gouge
Old stopes above level
Quartz on F.W.
Chance for high grade
Appears to widen above level 2' qtz. dike and sulphides
Spec. 4018
Sulphides and sil granite
ORE
FRESH DIKES
ORE
Some hydrothermal alternation. Qtz. sulphide shows slight sheeting
Qtz. sulphide and altered dike
Sp. galena free Au 4000
NAIL
#5767
82° H.W.
4' DIKE
SPAD
N58°E

FIG. 5.—GEOLOGY OF PORTION OF 200-FOOT LEVEL, TACOMA AREA.

FUTURE ORE RESOURCES

A knowledge of the origin of the veins and their relationship to the mineralizing system is valuable in planning future exploration. Geological features that appear to be of greatest significance in this respect are summarized as follows:

1. Development upon known structures has not been continued throughout their entire lineal extent. Additional drifting is expected to disclose new ore shoots.
2. Some structures disclosed in surface mapping are worthy of exploration. In accomplishing this, still other structures which are weak at the surface may be found.
3. The hypogene mineralization present is characteristic of low-temperature deposition, and its persistence to moderate depth is probable. The strength of vein structures is sufficient to permit moderate depth projections.

MINING METHODS AND COSTS

Recent History

In 1933 the present San Mauricio Mining Co. was formed by J. H. Marsman and associates. In February 1934 work was started to open the Ancla de Oro drainage adit. Simultaneously, geological reconnaissance work was conducted and several prospecting parties were put in the field. The San Mauricio, Imbong-Imbong, Santa Monica, Kansas, Brooklyn, Tacoma and Santa Ana veins were discovered as a result of this survey, and development work was started. Sufficient work was done on each vein to determine its size, extent, mineralization and character. The preliminary work was stopped late in 1934, and all development was centered on the San Mauricio vein area.

The 100-ft. level adit was opened and a drive was started to connect to the old shaft, which was reached in December 1934. The shaft was repaired, and the 200-ft. level was found open in all parts. The workings were sampled and the results checked the old assay plans and reports. Intensive development was started, and sufficient ore was found to warrant the construction of a 150-ton treatment plant, which was put into operation on March 10, 1936. It has been in continuous operation since that date and has been enlarged twice. The first increase was to 300 tons daily capacity in June 1937, and the second to 450 tons, in June 1939.

During a period of five years, San Mauricio has grown from a mere group of 104 claims to the third largest producer in the Philippine Islands. Dividends, amounting to approximately 130 per cent of the original capitalization, have already been paid to the stockholders. Ore reserves as of Jan. 1, 1939, totaled 315,800 tons with a contained value of ₱15,671,500 ($7,835,750).

General Mine Description

The San Mauricio operation is divided into three mining divisions, the San Mauricio, the Spokane, and the Santa Ana.

San Mauricio Division.—The San Mauricio division, which includes the San Mauricio and Tacoma sections, is the largest and is served by the Main shaft as an extraction shaft and the San Mauricio shaft for supplies.

Mining in this division is in progress on the 200, 300, 400 and 500-ft. levels of the San Mauricio, Tacoma No. 1, Tacoma No. 2, Tacoma No. 3, Tacoma No. 4, Tacoma 1990, Tacoma 2135, and Contact veins.

In the main shaft three compartments have been sunk to a depth of 800 ft., with stations on the 500-ft. and 750-ft. levels. A 350-ton pocket has been cut on the 500-ft. level, from which all ore hoisting is done. This pocket is equipped with air-operated gates and measuring pockets. The ore is drawn through the measuring pockets into 3-ton self-dumping skips and hoisted to the mill bins. Hoisting is done with an Allis-Chalmers double-drum electric hoist powered by a 200-hp. slip-ring induction motor with rope speed of 600 ft. per minute. The hoist has oil-operated brakes and clutch engines, and complete Lilly safety control equipment. At present 350 tons per day is hoisted through this shaft. The headframe is of steel.

The Tacoma section will be worked below the 500-ft. level by means of an interior shaft. It will be a two-compartment shaft through which the ore will be hoisted in cars and dumped into a pocket above the 500-ft. level. The ore will be trammed to the Main-shaft ore pocket in trains of ten 2-ton cars drawn by storage-battery locomotives.

Spokane Division.—The Spokane division, which includes the Spokane, Santa Monica and Imbong-Imbong sections, will be worked through the Spokane shaft, which is now being sunk. The first station will be at 400 ft., which corresponds to the 200-ft. level at San Mauricio. The Spokane division is being worked at present only on the 200-ft. level of the Spokane vein. This division is about 1000 ft. east of the San Mauricio and Tacoma vein areas.

Santa Ana Division.—The Santa Ana division, which includes the Santa Ana, Kansas, and Turayog sections, is about 4000 ft. east of the Spokane, and is worked through the Santa Ana shaft. The Santa Ana section is worked on the 150-ft., 300-ft. and 425-ft. levels of the Santa Ana vein. The 550-ft. station is being cut. The Turayog, or hanging-wall vein, will be intersected in the near future by a crosscut on the 300-ft. level. The Santa Ana No. 2, or footwall vein, will be cut later, when facilities of the mine permit. The equipment at this shaft consists of a double-drum Joshua Hendy hoist equipped with a 50-hp. motor having a rope speed of 250 ft. per minute. The safety equipment consists of an automatic solenoid brake with an overwind cutout. A steel headframe is being erected and the ore will be hoisted in 1-ton cars on a double-deck cage; 100 tons per day is hoisted through this shaft.

Level Spacing

Main shaft levels will be spaced at 250-ft. intervals, as that distance has proved to be the most economical for many reasons. If stations are cut at closer intervals, the cost of cutting the shaft stations, crosscutting to the veins, and the installation of pumping stations would be greatly increased.

In the future, mining levels will be run between them at 125-ft. intervals, and will be driven through the ore shoots from raises above the main levels. Handling supplies and men through well equipped raises for this distance presents no difficulties. In the past, levels were cut at 100 ft., so that sufficient ore could be mined to meet mill capacity.

Capital Development

Capital development at San Mauricio consists of main haulage-level drifting, shaft sinking, shaft stations, ore pockets, drainage adits, crosscutting on main levels, ventilation raises, and ore passes.

At present about 1400 ft. of such development is done per month. It amounts to 0.14 ft. per ton of ore milled. The approximate cost is ₱3.20 ($1.60) per ton of ore milled.

Cost per foot for capital development is ₱21.00 ($10.50). This includes drifting (78 per cent), crosscutting (17 per cent), and shaft sinking (5 per cent) of the total footage. Distributive charges are included in the costs.

Drifting.—Drifts are 5 by 7 ft. in cross section and are driven without timber. The vein material is firm and medium hard. Drilling and blasting are done on one shift and mucking on the other. About 5 ft. of advance per day is made at a cost of ₱17 ($8.50) per foot. Advance per man-shift is ½ ft. Drifter machines (3½ in.) are used for drilling; all mucking is done by hand. Forty per cent dynamite with both electric and hand firing is used. The normal crew is one "capataz," two miners, one helper, and one nipper, on the drilling shift and two muckers and three trammers on the mucking shift. Costs for March 1939 are listed in Table 1.

Crosscutting.—Crosscuts are 6 by 7 ft. The rock is very hard granite gneiss, and two 3½-in. drifters are necessary to finish a round in a shift. As in drifting, drilling is done on one shift and mucking on the other. An average advance of 4 ft. per day is maintained at a cost of ₱22 ($11) per foot. Advance per manshift is ⅓ ft. The normal crew is one capataz, two miners, one helper and one nipper on the drilling shift and two muckers and three trammers on the mucking shift. Costs for March 1939 are listed in Table 1.

Shaft Sinking.—The main extraction shaft has three compartments, each 5 ft. by 4 ft. 9 in. The rock is a siliceous gneissoid granite, which is very hard to drill. Three-inch drifters with handle bars are used. Bench rounds are drilled to prevent blasting out the timber, which is 10 by 10-in. Oregon pine. Mucking is done with a mucking pan, which dumps into a car on the sinking cage. The cage can be lowered to the bottom at any time, as extension shoes are used. This installation has been very satisfactory and has speeded up sinking to the present advance per man-shift of 0.07 ft.; formerly, it was 0.035 ft. per man-shift. The normal crew is one hoistman, two topmen, one capataz and eight miners per shift. Work is continuous, and an American foreman is in general charge of the three shifts. The cost per foot is slightly less than ₱85 ($42.50), as is shown in breakdown in Table 1.

TABLE 1.—*Costs per Foot*

Item	Drifting	Crosscutting	Shaft Sinking
Labor	₱ 3.64	₱ 5.10	₱29.21
Explosives	3.20	6.80	13.11
Timber		0.13	16.37
Miscellaneous supplies		0.04	13.62
Power	1.61	1.72	1.78
Engineering	0.51	0.33	0.53
Assaying	0.43	0.22	
Supervision	1.33	1.33	1.50
Mine distributive	6.73	6.62	7.20
Total	₱17.45 ($8.72)	₱22.29 ($11.14)	₱83.32 ($41.66)

Operating Development

Operating development includes all work on veins other than that covered by Capital Development or Stoping.

Raises consist of two cribbed compartments, their inside dimensions being 3 by 3 ft. One is used as a chute, the other as a manway. Pipe lines are carried up the manway. The regular crew for driving raises consists of two miners and a helper. Advance is about ¼ ft. per man-shift.

Operating development cost averages ₱20 ($10) per foot, or ₱0.82 ($0.41) per ton of ore milled.

Stoping

Stoping raises are spaced at 100 ft. in the ore shoots, and are used for entries and ore chutes, and as passes for fill from the levels above.

In starting a stope in high-grade areas a cut is taken from the back of the drift and timbers are placed to work from and to hold the fill after stoping. In the lower-grade areas a pillar about 5 ft. thick is left over the drift, to avoid timbering. In addition to the regular raises at 100-ft. spacing, which are used as chutes, intermediate chutes midway between the stoping raises are carried up with the stopes. This provides ore chutes on 50-ft. centers.

TABLE 2.—*Summary of Costs*[a]

Item	Operating Development		Stoping[c]	Mine Department General Expense	Total Mine Operating[d]	Development	Mill Operating	Mine General Expense
	Per Foot[b]	Per Ton Milled	Per Ton Milled	Per Ton Milled	Per Ton Milled	Per Ton Milled	Per Ton Milled	Per Ton Milled
Labor	₱ 3.69	₱0.15	₱0.63	₱0.23	₱1.01	₱0.71	₱0.28	₱0.70
Supplies	6.35	0.26	0.75	0.14	1.15	0.73	0.82	0.35
Supervision	1.33	0.05	0.26	0.02	0.33	0.18	0.31	0.45
Mine distributive	6.21	0.25	1.26		1.51	0.90		
Power	1.58	0.06	0.32		0.39	0.23	0.40	0.07
Assaying	0.56	0.02	0.04		0.06	0.06	0.05	
Engineering	0.47	0.02	0.09		0.11	0.07		
Cash disbursement								0.09
Total	₱20.19 ($10.09)	₱0.81 ($0.40)	₱3.35 ($1.67)	₱0.39 ($0.19)	₱4.56 ($2.28)	₱2.88 ($1.44)	₱1.86 ($0.93)	₱1.66 ($0.83)

SUMMARY

Mine operating	₱ 4.56
Mill operating	1.86
Mine general expense	1.66
Capital development	2.88
Smelting	3.00
Grand total	₱13.96

[a] Costs shown do not include taxes, depreciation or general overhead, but do include all general expense at the mine.

[b] 0.40 ft. per man-shift.

[c] 1.2 tons per man-shift.

[d] Includes operating development, stoping and Mine Department general expense. 1.0 tons per man-shift.

At the San Mauricio mine either the hanging wall or the footwalls of the Tacoma and San Mauricio vein are usually shattered, and a cut-and-fill system of mining with the stopes well filled at all times is essential. Fill is secured from development work that is in waste, and from "dog holes" driven into the stope walls. These "dog holes" serve two purposes; exploration and filling. The veins are fairly high grade and in places extremely high-grade narrow stringers pass into the walls. They may be found by crosscutting, since intersections are usually obscure. Several important ore bodies have been found with such crosscuts for fill, and recently a large zone of very good ore has been opened between the Tacoma No. 3 and No. 4 veins.

One hundred feet or less along the vein constitutes a stoping section. The actual extraction of ore is done by a stope capataz and a crew of men, who work under the close supervision of a level capataz and an American shift boss. Clean mining is enforced with a very close assay control.

Ore from the various stopes on the different levels is hand-trammed to ore passes, where it is transferred to the main haulage level and thence trammed to the ore pocket at the main shaft.

At the Santa Ana mine the hanging wall is good, and rill stoping is used with a considerable reduction in cost. Ore is hoisted in 1-ton cars to storage ore bins and from those trucked to the mill bin, a distance of 3.5 km. at a cost of ₱0.60 ($0.30) per ton.

Summary of Production and Development

From the start of operations in 1936 to the first of June 1939, production and development were as follows: tons milled, 271,909; total contained value, ₱11,289,360.30; average heads per ton, ₱41.52; total recovered value, ₱10,499,105.15; average recovery per ton, ₱38.62; extraction, 93 per cent; capital development, 35,947 ft.; operating development, 11,774 ft.; total development footage, 47,721.

MILLING HISTORY AND PRACTICE

The upper portion of the San Mauricio ore body contained considerable copper, and was thoroughly oxidized in places. This is true of the district in general, although the average percentage of copper content at San Mauricio has always been less than at the other mines. For this reason the mill when first built combined gravity and flotation. The usual ore is fairly high in sulphide content and contains pyrite, chalcopyrite, sphalerite, and galena. The copper content has decreased while the zinc content has increased.

The gold recovered by gravity processes has ranged from 7 to 12 per cent of total recovered value. This indicates a physically fine gold deposition and intimate association with sulphide minerals, and explains the abnormally low recoveries obtained in early-day mill operations in the San Mauricio area. Indeed, all engineers' reports comment on the refractory nature of the ore.

During the first years of operation of the mill the concentrate was shipped abroad for treatment at considerable cost. Since the ores contained some 15 per cent of total sulphides, efforts were made to float a copper-lead concentrate carrying gold and silver values, and to depress worthless iron and zinc sulphides.

This selective flotation was never very successful at San Mauricio for the reason cited above, and it was found that whenever pyrite was depressed in flotation the recovery was lowered. Present practice, particularly since the building of the smelter in the district, embodies bulk flotation of all sulphides. This practice, and the cleaner sulphide ores from deeper mining, have improved recovery, so that from 93 to 95 per cent of gold value contained in the heads is recovered. Present ratio of concentration is between 14 and 15 to 1.

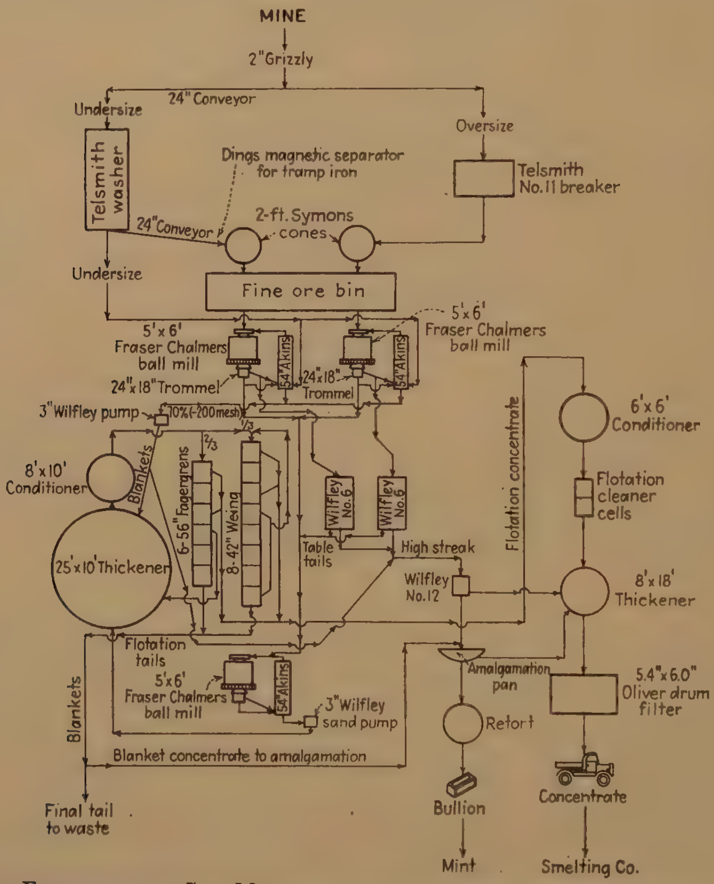

FIG. 6.—FLOWSHEET OF SAN MAURICIO MILL. 450 TONS PER DAY, APRIL 19, 1939.

The flowsheet of the San Mauricio mill (Fig. 6) is largely self-explanatory. The ore delivered from the mine is always wet and contains some clay or gouge. For this reason the cars are dumped over a 2-in. grizzly. The undersize portion passes through a Telsmith washer, thus by-passing the primary crusher. Washer undersize runs to mill classifiers, and oversize joins primary crusher discharge, and is crushed to minus ½ in. in two 2-ft. Symons cone crushers. The two primary 5 by 6-ft. Fraser and Chalmers ball mills operate in parallel on ½-in. feed, in closed circuits with two 54-in. simplex Akins classifiers.

A portion of the discharge from the two primary mills, passing through trommel screens, feeds two No. 6 Wilfley tables. These table tailings and a portion of the two primary mill discharges are fed to the classifier on the third ball mill. All classifier overflows go to a 10 by 10-ft. conditioner and then to two banks of flotation machines, which operate in parallel. One bank consists of six 56-in. square Fagergren machines, and the other of eight 42-in. Weinig machines. The concentrate from the first two or three machines on each bank goes to a 6 by 6-ft. conditioner, and then to two square 24-in. Fagergren machines for cleaning. The cleaner tailing and middling from remaining machines on both primary flotation banks are pumped to a 25 by 10-ft. thickener, which acts as a surge tank only. From here this pulp is returned to the conditioner to join flotation feed.

The final concentrate is thickened and filtered and shipped by truck to the smelter.

The concentrate from the two No. 6 Wilfley tables is reconcentrated on a No. 12 Wilfley table. The tailing from this table joins final flotation concentrate. The table concentrate is amalgamated in horizontal pan amalgamators. The amalgam is retorted, the sponge is melted to bullion, which is shipped to the United States Mint at San Francisco.

Reagents used in flotation average approximately as follows: amyl xanthate, 0.2525 lb. per ton ore; Aerofloat, 0.113; pine oil, 0.125; soda ash, 0.24 to 1.6; cyanide, 0.59; sodium silicate, 0.3555.

Metallurgical Experimental Plant

A 10-ton pilot mill is under construction at San Mauricio, to be used for thorough, closed-circuit, cyanide test work on San Mauricio and other ores. Cyanide tests will be conducted on flotation tailing, flotation primary machine discharge, and mine-run ore, in order to determine by closed-circuit, continuous test whether the cyanide process will be economical, either with or without preliminary removal of copper. As the copper content has decreased at depth, it may not preclude cyaniding. The zinc content has increased so markedly that the pilot mill was considered the most logical step in order to operate a closed-circuit test. In this way the cumulative effects of various impurities will be determined, not only on the dissolving of gold but also on precipitation.

Pumping and Drainage

Water is not a serious problem at San Mauricio, but the great number of old workings that connect to the surface made continuous heavy pumping a necessity during the rainy season and typhoons. As it was practically impossible to find and block off these openings, because they had been completely covered with dense tropical jungle, it was decided early in 1938 that a drainage adit was necessary, and the Reed adit was driven in from about 50 ft. above sea level and connected to the 200-ft. level. This takes care of all surface water; all water from the lower levels is pumped to this adit, with a reduction in pumping head of 200 feet.

The main pumping plants of the San Mauricio division are on the 500-ft. level at the Main and San Mauricio shafts, to which all mine drainage below the 200-ft. (drainage adit) level is brought, from whence it is pumped to the drainage adit. The normal flow of water is 450 gal. per min. in the dry season and 600 gal. per min. in the wet season.

Engineering Department

The engineering department is responsible for the underground and surface surveying, sampling, sample records, ore estimation, the design of all structures, road building and upkeep, and the administration of the company barrios.

Sampling is an important item at San Mauricio and is closely watched. All working faces on veins are sampled daily by well cut channels. Grab samples are taken from every muck pile and rushed through the assay office in order to better control the ore going to the mill. Grab samples are taken from each car delivered to the ore passes and are kept separate as to working places. These samples check closely with the general mill-head sample.

Additional data on sampling during May 1939 are as follows: tons milled, 12,500; total samples, 4263; total feet cut, 6740; total feet cut per day (average), 217.5; total samples per day (average), 137; cost per sample, ₱0.105; cost per foot cut, ₱0.066; cost per ton milled, ₱0.039.

Geological Department

The geological department is under the direct supervision of an American geologist, who personally maps the advances, brings maps up to date twice monthly, studies ore occurrences, and recommends development.

Two prospecting crews are constantly maintained. A surface prospecting crew works selected areas in detail, and plots pits, colors and float on a map. A geoelectrical party prospects by a modified single leap-frog method based on relative resistivity along traverse lines. A project of contouring the granite surface below the cover by geophysical means is under consideration. Results are being obtained by both methods now in use.

Assessment work is handled by a foreman under the direct supervision of the geologist, who outlines the work to obtain geological information. Assessment crews are maintained throughout the year. and the work proceeds with a minimum of wastage and a maximum of information. Tunnels, trenches and pits are located on the map and records kept of the work done.

Assaying

The assay office and chemical laboratory at San Mauricio, while not the largest, is the most complete in the Philippines. It is completely equipped for the analysis of ores, concentrates, mattes, base-metal alloys, iron and steel, coal and coke, water and many other kinds of analysis too numerous to mention. One of the most useful pieces of equipment is a 48,000-line spectrograph, with which any known inorganic substance can be analyzed. Samples from all over the Orient are received for determination by the use of this instrument.

The office is in charge of an American chemist, who has 15 native helpers. An average of 7500 determinations are made each month.

Power

Power is generated by six solid injection, airless, four-stroke cycle, force-feed lubricated Allen Diesel engines driving six alternators, which develop 2300 kva. at 480 volts. Table 3 gives the power cost analysis.

The power plant is under direct supervision of a plant foreman, who works under the orders of the Power and Mechanical Superintendent. The operating crews consist of an operator and two wipers on each shift with the addition of two mechanics and two helpers on the day shift.

Mine Safety

The installation of strict safety measures became a necessity at the outset of operations. Since the native labor employed at the beginning had little or no experience in mining, an intensive campaign of instruction in efficiency and safety had to be instituted. This immediately became a problem, for, although most of the present generation of Filipinos speak, read and write English, they do not understand the American version of it, and it was difficult to give instructions understandable to all of the employees.

No regular safety engineer was employed, but the work of this nature was carried out by the mine superintendent with the assistance of the rest of the staff. Regular meetings of the capataces were called every two weeks with the superintendent or one of the foremen in charge. These meetings were similar to grade-school classes with the teacher working through an interpreter. Lessons were assigned at each of the meetings, and the capataces studied them and recited at the next meeting. The problems discussed in these lessons were all fundamentals of mining methods and safety precautions. This system was greeted with enthusiasm by the men, as the Filipino of this type is always anxious to learn.

There are, however, many obstacles to overcome in teaching a Filipino to be "safety minded." The greatest of these is his natural fatalistic attitude, which works directly against the idea of guarding against future accidents. The campaign toward safety is unceasing; results are now being obtained, not by training the miner's mind to guard against accidents but by putting accident prevention into the regular routine of his work. This routine work includes barring down, inspection of hoisting equipment, tracks, manways, electric blasting; a compulsory report of missed holes wherever possible, and a thorough control of ventilation. If these are carefully watched, the mine is in a safe condition. Hard hats have been made compulsory and there has been a corresponding reduction in head wounds. At present the campaign to get the miners into shoes or boots of some sort is having some effect and, as a result, foot wounds are less frequent.

TABLE 3.—*Power Cost Analysis*

KILOWATT-HOURS GENERATED, 2,532,345

Costs per Kilowatt-hour Produced

Supplies	Total	Per Kw-hr.
Crude oil	₱31,384.48	₱0.0124
Lubricants	5,594.00	0.0022
Spare parts	2,531.28	0.0010
Leakage	2,531.00	
Miscellaneous	1,188.65	0.0005
Total supplies	₱40,698.41	₱0.0161
Labor	3,270.67	0.0013
Supervision	1,200.00	0.0005
Total power cost	₱45,169.08 ($22,584.54)	₱0.0179 ($0.00895)

KILOWATT-HOURS PER TON MILLED

Operating development	3.382
Stoping	17.017
Mine operating	20.399
Capital development	12.087
Milling	20.657
Mine general expense	3.955
Total	77.497
Cost per kilowatt-hour	₱0.0179 ($0.00895)

A safety bonus of one day's pay is paid to all capataces for each 300 man-shifts of work without a lost-time accident by men working under his supervision. This is getting results.

Recently, in cooperation with the Philippine Bureau of Mines, a Safety Association was formed by a majority of the operating mines in the Mambulao-Paracale district. A capital appropriation was made to build and equip a modern safety station. Technical equipment, including self-contained breathing apparatus for use in combating mine fires; gas testing equipment; anemometer and allied equipment; first-aid training materials; and incidental equipment pertaining to safety work were purchased, with a truck for transporting the equipment.

The Director of the Association has as his duties: monthly inspections of all mines in the Association, with reports to the management of the results of these inspections and recommendations for improvement of safety conditions; ventilation studies of the mines; investigations and reports on all serious accidents; keeping statistics and charts on all serious accidents, minor or major, in all mines in the Association; training in first aid and mine rescue; holding safety meetings with mine capataces and staffs of the several mines.

TRAINING OF LABOR

Mining is an industry that requires a large supply of skilled and unskilled labor and in 1934, when serious development work started at San Mauricio, there was very little unskilled labor to be had and skilled labor was nonexistent in the district.

The Bicol region, particularly Camarines Sur and Albay, offers an almost unlimited supply of unskilled labor. From this supply were developed foremen, capataces, miners, timbermen, shaftmen, trackmen, and pipemen, to say nothing of muckers, trammers and others rated as unskilled underground labor.

Great care was taken in the selection of capataces, and only men were selected who in addition to being leaders of their groups were also men of at least grade-school education and men with some natural initiative. In the selection of capataces no attention was paid to any previous mining experience. It was preferable to teach them methods that were applicable to larger scale operations than any they had been familiar with. Considerable time was spent in teaching them the rudiments of mining and underground safety measures, classes in mining and allied subjects being held every two weeks.

These classes of instruction for the capataces were open to miners also and were compulsory for men looking forward to promotion. The instruction ranged from a simple glossary of mining terms to the study of hard mining problems and was given by the various mine foremen and the mine superintendent. A different problem was discussed at each meeting. The material for a thorough study of it was compiled by one of the foremen, and a brief outline of the subject was prepared with 10 questions and answers. These questions and answers were gone over in class and each man had to be thoroughly prepared to answer any question asked him on the subject at the next meeting.

Labor is hired with the greatest possible care and, with the exception of skilled mechanics and millmen, every man that is selected for employment is looked upon as a potential miner. Even though a man may be hired to do surface labor, he understands that he will be moved into the mines at the first opening.

A very thorough examination is now made of the qualifications of every applicant for employment and a very rigid medical examination is required. After employment every effort is made to fit a man into the job for which he is most suited, in order to allow him to earn a maximum wage.

Local labor is seasonal and from the start of operations the management endeavored to build up a skeleton crew of men that would weather all the fiestas, seasonal plantings, harvests, and other diversions to which Filipino labor is addicted. To date there has been little lost time or decrease in production due to labor shortage.

An efficiency bonus is paid to all men working on development work. Efficient work will earn a bonus equivalent to 25 per cent of a man's wages, or more. In order to get into this branch of mining, a man usually must put in at least four months in the various other branches of the work before he is eligible for the development crews. Shaftmen, who are the best paid of all mining labor, are selected when possible from these development men. All of this inducement by means of higher wages tends to keep men on the job, although the labor turnover is still fairly high. The average wage scale at San Mauricio has increased from 90 centavos per day in 1934 to ₱1.51 per day in 1939, or an increase of 68 per cent in 5 years.

Hospital and Medical Department

San Mauricio, together with the United Paracale Mining Co. and Coco Grove, Inc., owns a splendid modern hospital (Marsman General Hospital), a model for any mining community. It owns modern surgical and medical appliances and is staffed with capable surgeons, physicians, nurses, and a pathologist. Approximately 3000 men and their families are looked after by this hospital.

Special attention is given to tropical diseases and diseases that are prevalent among the native employees. Many of these diseases, especially malaria and dysentery, have been almost eradicated.

A strong effort is being made to interest the native mothers in baby feeding. Some results are being obtained, but this will probably require years of effort.

All accident cases due to employment, all occupational diseases, and in addition, malaria and dysentery, are treated free of charge. Families of employees are treated at cost for any medical or surgical needs.

Carbon Dioxide Accumulations in Geologic Structures

By J. Charles Miller,* Member A.I.M.E.

(New York Meeting, February, 1937)

Natural carbon dioxide has recently been exploited in the United States in consequence of oil and gas developments in the Western States and the growing demand by transcontinental and transoceanic shippers for solid carbon dioxide. The discovery by drilling of commercial deposits resulted in consideration of its geographic and geologic distribution and occurrence. Its wide distribution in nature is evidenced by its occurrence in the atmosphere, hydrosphere and lithosphere. The question of origin of carbon dioxide involves consideration of theories similar to those concerning natural hydrocarbons, although available evidence favors an inorganic rather than an organic source. Areas favorable to development of commercial production appear to be those in proximity to igneous rocks or in the vicinity of decadent volcanic activity, where, it has long been known, the gas is evolved either free or dissolved in the waters of fumaroles, geysers or mud pots. Structure contour maps are presented showing the Wagon Mound anticline in New Mexico and the Farnham anticline, Utah. A well drilled on the latter supplies gas to a 20-ton plant manufacturing solid carbon dioxide at Wellington, Utah, on the Denver and Rio Grande R.R., whence it is shipped to surrounding territory and to the West Coast. Before funds are invested in a plant for the manufacture of liquid or solid carbon dioxide, whether supplied by wells or springs, an effort to ascertain the volume of gas available is advisable. The use of present methods of estimation of gas reserves with modifications to account for the quantity absorbed by any water present in the producing formation is recommended. The Farnham anticline is used as an example and computations are made of the probable volume of gas originally present in the structure. No attempt was made to compute reserves in the Niland area, California, for the reason that in such areas it is believed the volume is indeterminate.

Introduction

Carbon dioxide, in liquid and solid form, has found a wide variety of uses other than its primary application in carbonating beverages. It is now used in more than 40 different ways, ranging from cooling or freezing to use in gas or liquid form for mechanical purposes, chemical industry, explosive, fire extinction, and tire manufacturing. Undoubtedly the chief supply of carbon dioxide is obtained from industrial plants or artificial sources and until recently natural deposits of the gas have received little consideration. Few will question the utility and perhaps dependability of artificial sources, which possess the advantage over

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many natural deposits of being situated at or near the point of consumption. This advantage of location pertains chiefly to the solid, which evaporates continuously, consequently long storage and shipment are not conducive to economic marketing. In some of the Western States, and perhaps in some foreign countries where natural sources or accumulations may be present, and where coal or by-product gas is not available, consideration of geological conditions requisite to commercial deposits provides a means of determining the feasibility of exploiting such occurrences.

HISTORICAL REVIEW

The presence of carbon dioxide in the free or combined state in springs has long been recognized, and perhaps the first mineral springs to attract the American colonists were those at Saratoga, N. Y., which according to Kemp[20] were known as early as 1767. These waters usually issue from the wells or springs at temperatures between 50° and 54° F., slightly above the annual mean temperature. The natural flow of the springs was utilized until about 1870, when the first well was drilled. During the period between 1892 and 1905, when it was realized that the carbon dioxide in the mineral waters could be extracted profitably, more wells were drilled. Competition between the producers of carbon dioxide resulted in excessive drilling and pumping of wells, so that between 1910 and 1912, before pumping was stopped, approximately 400,000 gal. of mineral water[4] was pumped daily. The water level is reported to have been lowered 100 to 150 ft. by this overdraft. The gas is found at depths of 150 to 600 ft. and at the flush period of production 30 or more wells contributed to the supply. During the most active period, between 1904 and 1908, the annual production of carbon dioxide ranged between 4,000,000 and 5,000,000 lb. per annum. In 1927 the State received royalties totaling about $15,000 from gas produced on the State Reservation.

Until the creation of the State Reservation at Saratoga and legal restraint from pumping in 1908, the compression of carbonic acid gas was an important industry at Saratoga Springs and in the vicinity. This was one of the first important natural occurrences to be used exclusively for carbonic acid production, and undoubtedly it demonstrated the feasibility of utilizing similar supplies. Nevertheless, a number of years elapsed before the natural gas from wells again attracted attention.

In 1926 the Continental Oil Co. completed a well on the McCallum anticline, near Walden, Colo., in the NW.¼ NW.¼ of sec. 12, T.9N., R.79W., 6th P.M., which produced, according to reliable estimates, 50,000,000 cu. ft. of carbon dioxide gas with a few barrels of oil of 45.8°

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[20] References are at the end of the paper.

A.P.I. gravity. An experimental plant for the manufacture of solid carbon dioxide was constructed in the field in 1930 but this was dismantled in the summer of 1932. This discovery appeared to stimulate interest in natural carbon dioxide from wells, and in June 1930 the Carbon Dioxice and Chemical Co. completed a carbon dioxide well on the Farnham anticline in the SW.¼ of sec. 12, T.15S., R.11E., S.L.M., Utah. In 1931 the Estancia Valley Carbon Dioxide Development Co. commenced drilling a well for carbon dioxide in the SE.¼ SE.¼ of sec. 12, T.7N., R.7E., N.M.M., Wilcox anticline near Estancia, N. M. Late in 1932 the Salton Sea Chemical Products Corporation commenced drilling a well for carbon dioxide near Niland, in Imperial Valley, Calif., in the SW.¼ of sec. 28, T.11S., R.13E., S.B.M. Plants for the manufacture of solid carbon dioxide were subsequently constructed in each of the last three localities named.

Distribution in the United States

Geographic.—An interesting table by Dr. Peale[29] illustrates the frequency of mineral springs in the United States and discloses a preponderance of such springs in the western United States. Peale states that there is a far greater prevalence of thermal springs in the West than in other sections, and that many of them are carbonated. Analyses of their waters often reveals an abundance of carbon dioxide either in the free or the combined state. The geysers and springs of Yellowstone Park are known to contain large volumes of the gas. It is worthy of note that Rogers (ref. 32, p. 119) reported analyses of gas from springs in France ranging from as much as 41.5 to 99.8 per cent carbon dioxide. An old fumarole at Agnano, near Naples, Italy, representing Vesuvius gas, and that emitted by a hot spring in Iceland he reports contain 96.52 per cent and 79.5 per cent carbon dioxide, respectively. It is generally recognized that natural gases from wells in this country containing noteworthy amounts of carbon dioxide are confined chiefly to the western United States. Lang[21] discussed two of the early discoveries of carbon dioxide gas in wells drilled in New Mexico and probably was the first to suggest a causal relationship between these large quantities of the gas and the results of igneous activity in northeastern New Mexico. Dobbin[13] discussed the occurrence and origin of carbon dioxide gas in the United States and other countries, citing wells in fields or areas in Montana, Colorado, New Mexico, Utah and California. The wells near Niland, Calif., at the southern end of the Salton Sea, which supply gas to two plants in that vicinity, were discussed in a previous paper.[27] Rogers states (ref. 32, p. 37) that some natural gas produced in California contains unusually high percentages of carbon dioxide, carrying "as much as 49 per cent of carbon dioxide, and a great many contain 10 or 15 per cent . . . but true natural gas containing noteworthy proportions of this constituent occurs almost wholly in California."

Geologic.—Carbon dioxide has been discovered in the United States in wells drilled into rocks ranging in age from Cambrian to Tertiary. Its source in springs is not easily determined but an exhaustive investigation of the geysers and springs and of boreholes in Yellowstone Park by Fenner,[14] Allen, Day and Merwin[2] has thrown much light on the possible age and character of its source rocks. Its wide distribution or occurrence is related to its function in natural processes.

OCCURRENCE

Carbon dioxide is present in the free or combined state in the atmosphere, hydrosphere and lithosphere. Commercial accumulations are confined largely to the lithosphere, and the waters and gases issuing from springs. Some, however, becomes trapped in geologic structures and may be obtained only by drilling. These are at present the chief natural sources of commercial interest. Clarke[9,10] has considered carbon dioxide in his Data of Geochemistry and in the present paper frequent reference has been made to that publication and to the literature that he reviewed.

Atmosphere.—The present atmosphere has little bearing on commercial accumulation of the gas but its origin is intimately connected with the origin of the globe. For this reason the discussion of the atmosphere has been included.

Air consists roughly of four-fifths nitrogen and one-fifth oxygen, but carbon dioxide content is very nearly uniform and normally present in the atmosphere to the extent of three volumes in 10,000. If the rate of generation of carbon dioxide by combustion of coal and other substances were constant and no disturbing factors interfered, the amount of it in the atmosphere would be vastly increased over a period of time. The large factors tending to maintain a balance are: (1) the decomposition of carbon dioxide by plants, with liberation of oxygen, (2) the consumption of carbon dioxide in the weathering of rocks, and (3) absorption by surface waters. The liberation of oxygen began with the appearance of low forms of plant life, possibly reached a maximum during the Carboniferous era, and since has diminished. Clarke points out, however, that two opposite views of the composition of the primitive atmosphere have been taken: (1) that it was rich in oxygen, and (2) that it was oxygen free. He further states (ref. 9, p. 57) that:

> The balance or lack of balance between carbon and oxygen is, after all, only one factor in the problem. The origin of the atmosphere as a whole is a much larger question and our answers to it must depend upon our views as to the genesis of the solar system. If we accept the nebular hypothesis, we are likely to conclude that the atmosphere is merely a residuum of uncombined gases which were left behind when the globe assumed its solid form. That seems to be the prevalent opinion, although it must be modified by the observed facts of volcanism.

In regard to the primitive atmosphere Clarke says (ref. 9, p. 55):

> The accumulations of carbon in the lithosphere such as the coal measures, the limestones, and the like, have led some geologists to assume that the atmosphere at some former time was vastly richer in carbonic acid than it is now; but the fossil records of life suggest that the differences could not have been extreme. With a large excess of carbon dioxide, the existence of air-breathing animals would be impossible. Only anaerobic organisms could live. It is clear that the stored carbon of the sedimentary rocks was once largely in the atmosphere but was it ever all present there at any one time?
>
> Such a supposition is improbable. The known carbon of this lithosphere, if converted into carbon dioxide, would yield nearly 25 times the present mass of the entire atmosphere and the atmospheric pressure at the surface of the earth would be enormously increased.

Several theories have been advanced to account for the source of carbon dioxide in the atmosphere by Hunt,[17] Meunier,[26] and others who postulated either a cosmic or a volcanic source, but Clarke holds that "A cosmical atmosphere has no assignable limit; an atmosphere of volcanic origin must sooner or later be exhausted."

Another theory relative to the atmosphere, favored in varying degrees by Koene, Phipson, Lemberg, Stevenson and Kelvin, is based upon the belief that the unoxidized but oxidizable substances in primitive rocks are sufficient in quantity to absorb all oxygen of the air.

The effect of atmospheric carbon dioxide and that in the free or combined state in the ocean, therefore, has an important bearing on discussions of theories of origin of carbon dioxide in geologic structures. In certain theories of climatic changes extraordinary importance is attached to variations in the amount of carbon dioxide in the atmosphere. Periods during which the carbon dioxide content of the atmosphere was high are considered to have been uniformly warm, those in which it was low are considered to have been times of cold weather or glacial periods. Brooks[5] concludes that carbon dioxide can never have been an important factor in climatic variations. He admits, however, that there appears little doubt that variations in the quantity of carbon dioxide in the atmosphere during different geological periods were considerable. Bunsen's examination of air from rain water at different temperatures showed that it contains as high as 2.92 per cent CO_2 at 0° C.

Hydrosphere.—A river or fresh-water lake owes its composition to the streams or ground waters contributing to it, and, a river particularly, to the conditions existing in the terrane along its course. Carbonic acid of either atmospheric or organic origin is the most abundant of chemical agents in the lake or river waters. Hence carbonate waters are the most common and as the streams form the great continental rivers the carbonate type becomes more pronounced. When these river waters reach the sea the calcium carbonate may be deposited as limestone or calcareous shale, or it may be withdrawn as such by living animals to form shells. In addition to carbonic acid, other dissolved gases in ocean water are nitrogen and oxygen from the air. The oxygen maintains life of the marine organisms and then oxidizes the dead matter of organic origin. Free or half combined carbonic acid may be absorbed directly from the atmosphere, or brought down in rain; or from submarine volcanic springs. The carbonic acid content of vadose water or water falling on the surface as rain is too small to have any effect on accumulation at depth. The acid, however, may be liberated by chemical or thermal action of waters of deep-seated origin on limestone, dolomite or other rocks containing lime.

It has been estimated that the ocean contains from 18 to 27 times as much carbon dioxide as the atmosphere and it is considered the great regulative reservoir of the gas. This fact has given credence to the assumption that the gas may have been present in connate waters.

The waters from mineral wells or springs may be classed according to their negative radicles as chloride, sulphate, carbonate or acid waters. The carbonates of calcium, magnesium, and iron are easily dissociated, giving carbon dioxide. Carbonate waters or waters of volcanic origin are of chief concern. The most notable springs or geysers of volcanic origin in the United States are those of Yellowstone Park. Allen, Day and Merwin[2] found that 7 out of the 40 Yellowstone gases analyzed contained less than 80 per cent carbon dioxide. Next to steam and carbon dioxide, hydrogen sulphide is the most important of the hot springs gases in Yellowstone. In addition to these, spring gases of volcanic origin may contain hydrogen, marsh gas, nitrogen and argon. Allen and Day calculated the composition of the uncontaminated permanent gases or original magmatic gas in the Yellowstone Park area as follows: CO_2, 98.26; H_2O, 0.11; CH_4, 0.11; $N_2 + A$, 0.86 and H_2S, 0.66. These investigators found that the alkaline springs gave a very small amount of gas, compared with other springs. Such springs are conspicuously high in nitrogen and methane. The bicarbonates of the alkaline springs are formed by the "absorption of magmatic carbon dioxide in chemical reactions below ground" (ref. 2, p. 510) thus reducing the volume of gas that escapes at the surface. In the acid or sulphate areas, on the other hand, abundant gases escape from the springs which contain little or no bicarbonate. Another difference between gases of sulphate and alkaline areas is the almost complete absence of hydrogen sulphide in the latter. Mud pots or mud volcanoes are simply extreme cases of the sulphate type of hot springs, the mud of which is composed of insoluble products of rock leached by acid water.

Lithosphere.—The effects of the dissolved volcanic gases on the rocks with which they come in contact are the formation of clays, replacement of soda and lime by potash and an increase in silica. If we assume calcium bicarbonate in solution, the changes due to escape of gas may be described according to the following formula:

$$CaH_2C_2O_6 = CaCO_3 + H_2O + CO_2$$

The result is the deposition of calcareous sinter. Clarke (ref. 9, p. 34) gives the weighted average composition of the lithosphere and calculates that CO_2 is present in combination with igneous rocks to the extent of 0.101 per cent, with shales 2.63 per cent, sandstone 5.03 per cent, limestone 41.54 per cent, or for a weighted average of igneous and sedimentary rocks to the extent of 0.35 per cent.

Bituminous shales and similar materials when heated give the products of dry distillation, such as hydrocarbons, especially marsh gas, carbon dioxide, ammonia and tarry matter. Limestone under similar conditions, that is, in the presence of intrusives, would yield carbon dioxide. However, these gases are common volcanic emanations occurring in many places where there is no positive evidence of the presence of limestone, sulphide deposits or organic materials.

Chamberlin[7] classified analyses of gases in igneous rocks according to age and found in his examination of rock samples heated in vacuo that there was a greater volume of gases in Archean rocks. He also noted "a rapid and steady decline in the quantity of every gas, in passing down the columns from the Archean through the Proterozoic and Tertiary to recent lavas." He assigns these differences to a combination of causes—older rocks may yield more gas than the recent, owing to metasomatic changes that have been slowly taking place within the rocks, or the early magmas may have been more highly charged with gas.

TABLE 1.—*Carbon Dioxide in Volcanic Gases*

Location	Date of Analysis	CO_2, Per Cent
Hawaii: The crater	1912	73.9
Sicily: Paterno spring of Vallancella	1865	99.78
Colombia: Purace solfatara	1868	98.2
Alaska: Katmai Nova Rupta Basin	1919	72.0
Canary Islands: Pico de Teyde north fumarole	1907	70.8
Java: Papandajan fumarole	1908	16.8 to 24.00

Analyses collected by Allen (ref. 1, pp. 70–80) show the percentages of CO_2 and other gases taken from different volcanic sources throughout the world. Although these analyses have little or no bearing on the quantity of the gas contained in igneous rock, they show the importance of carbon dioxide as a constituent of volcanic gases. It is interesting to note the percentages of carbon dioxide present in the volcanic gases selected from widely separated areas as given by Allen (Table 1).

In sedimentary and metasedimentary rocks, Chamberlin noted that age appears to make less difference in the gas evolved, although in these rocks, as in igneous rocks, carbon dioxide was present in large percentages.

He further noted from the analyses of gases from igneous rocks classified according to granularity that the fine-grained rocks yielded the largest quantity of gas. Gases in meteorites analyzed showed that carbon dioxide was more abundant in stony specimens than in iron meteorites. Besides carbon dioxide, occluded gases may occur in various rocks or minerals, and such gaseous inclusions contain quantities ranging from a trace to 98 per cent of hydrogen sulphide, sulphur dioxide, ammonia, nitrogen, marsh gas, methane, oxygen, argon and helium. Chamberlin[7] observes that "there is reason to suppose that at the depths where lavas originate hydrogen and oxygen exist combined as water, since up to temperatures of 2000° C. the dissociation of water takes place only to a limited extent."

An examination of available data on volcanic eruptions led Clarke (ref. 10, p. 292) to conclude that the certain regular order of appearance of volcanic gases is due to succeeding chemical changes and is essentially that laid down by Deville and Leblanc, except that the early evolution of hydrogen and carbonic oxide is taken into account as follows:

First. The gases issue from an active crater at so high a temperature that they are practically dry. They contain superheated steam, hydrogen, carbon monoxide, methane, the vapor of metallic chlorides and other substances of minor importance.

Second. The hydrogen burns to form more water vapor, and the carbon gases oxidize to carbon dioxide. From the sulphur, sulphur-dioxide is produced. The steam reacts upon a part of the metallic chlorides, generates hydrochloric acid, and so acid fumaroles make their appearance.

Third. The acid gases of the second phase force their way through the crevices in the lava and the adjacent rocks; their acid contents are consumed in effecting various pneumatolytic reactions. The rocks are corroded, and where sulphides occur hydrogen sulphide is set free. If carbonate rocks are encountered carbon dioxide is also liberated.

Fourth. Only steam with some carbon dioxide remains and even the latter compounds soon disappear.

These phases have been similarly described by others, including Delkeskamp,[12] who asigns a temperature of 1000° C. to the first phase, 600° to 100° C. to the second, and 100° to 50° C. to the third phase.

The statement is generally accepted that water vapor or steam forms 99 per cent of the entire gaseous output of volcanoes, particularly during the spectacular phase, but emanations of carbon dioxide with nitrogen and oxygen mark the last phase of volcanic activity.

ORIGIN

The occurrence of carbon dioxide is intimately connected with questions of its origin and accumulation in geologic structures; therefore any attempt to determine the origin of carbon dioxide in a particular locality leads to consideration of many possible sources of the gas and to realization of the complex factors that may contribute to its accumulation in commercial amounts. Two hypotheses of origin may be advanced to explain its source: (1) organic or sedimentary, and (2) inorganic or volcanic. To this some would add a third source, which may be related directly to the primitive atmosphere, but this is not considered an adequate source for commercial deposits.

Organic.—Carbon dioxide is derived largely from organic material consisting of the remains of planktonic organisms present in the water above the sediment and from other vegetable or animal matter contributed to the sea, the decay of which may be assisted by bacteria. During the decay of seaweeds, according to F. C. Phillips,[30] a little methane is at first evolved, but the generated gases consist largely of carbon dioxide, hydrogen and nitrogen. Organic matter may be deposited with the producing sand or in the adjacent beds. Retardation of organic decay by diminution of the supply of oxygen results in the formation of carbon dioxide from carbonaceous matter and the suppression of biochemical decomposition by diminution of the supply of oxygen may be caused by rapid deposition of sediments or by deposition beneath stagnant water. However, Trask[36] points out that the oxygen content decreases progressively with depth in buried sediments and the original organic source material decreases very greatly in quantity before it reaches the sea floor and is deposited in sediments. If the sea in which the sediments were deposited contained a high concentration of carbon dioxide and the atmospheric content at the time of deposition was relatively high, connate waters resulting therefrom may contain a relatively high amount of carbon dioxide. Under ordinary conditions the amount in sea water is slightly below that required for equilibrium with atmospheric carbon dioxide, and this is probably less than 0.1 gram per liter at ordinary temperature, according to Wells.[38] Other investigators have reported 0.023 per cent at 20° C. to 0.044 per cent at 0° C. Beyond a depth of 2500 fathoms, little calcium carbonate is found in sea water. The amount of free carbonic acid, however, increases slightly with depth. The origin of organic carbon dioxide is, therefore, closely allied to that of petroleum. Rogers[32] believes that much of the carbon dioxide in the California gas, for example, has probably been formed by oxidation of the hydrocarbons through contact with mineralized waters. The existence of large volumes of carbon dioxide in association with commercial accumulations of petroleum is further exemplified by the developments near Walden, Jackson County, Colorado, which were discussed in a previous paper.[28]

Inorganic.—The presence of carbon dioxide and ammonia on the planets has been determined by astrophysicists, and consideration of the possible sources of these gases in the earth, whether they be of cosmic, volcanic or organic origin is an involved subject. Moreover, carbon dioxide, ammonia and the sulphur gases are of too general occurrence to be connected invariably with the presence of bituminous shale, limestones, and comparatively superficial formations, for the local existence of which there is often little or no evidence. It is admitted, however, that these gases may find occasional access to the conduits of volcanic gases from outside sources. Allen (ref. 1, pp. 29–80) calculated the average composition of gases in igneous rocks based on Chamberlin's table (ref. 7, p. 27) of average volumes of various gases obtained from the igneous rocks per volume of rock, reduced to 0° and 1 atmosphere. Allen's Table 4 is given here as Table 2.

TABLE 2.—*Average Composition of the Gases in Igneous Rocks*
Calculated in Volume Percentages

Order	Type of Rock	Number of Analyses	Composition, Per Cent						
			H_2S	CO_2	CO	CH_4	H_2	N_2	Total
1	Basic schists	2	0.0	51.6	2.4	0.6	43.7	1.7	100
2	Diabases and basalts	14	2.6	53.8	6.0	1.6	34.5	1.5	100
3	Gabbros and diorites	11	0.4	48.8	2.7	1.5	44.2	2.4	100
4	Granites and gneisses	19	0.0	46.0	6.9	1.6	42.6	2.9	100
5	Andesites	7	0.0	77.8	7.5	2.5	8.4	3.8	100
6	Syenites	4	0.0	14.4	5.6	4.0	72.8	3.2	100
7	Rhyolites	4	0.0	79.3	5.7	2.3	6.9	5.8	100
8	Miscellaneous porphyries	2	0.0	40.5	7.6	5.1	41.8	5.0	100

Where the depth of burial of granitic masses is sufficient to reach a temperature of 400° to 500° C., carbon dioxide could be expelled at such points when the pressure of the gas is great enough to escape to points of reduced pressure if open fractures, crevices, or other openings exist. Van Orstrand has estimated[37] that this temperature is generally attained at depths of less than 12.4 miles. If a temperature gradient is 1° C. per 100 ft., the depth necessary to attain this temperature would be 36,000 ft., at which approximate depth no crevices or open fractures are likely to exist at present. It is worthy of note, however, that igneous intrusives, such as dikes, necks and other feeders or roots, contract upon cooling, and unless movement of strata occurs, surface waters may gain entrance to great depths, possibly 10,000 ft. or more. Spicer's recent computations[35] show that the boiling temperature of water is reached in one-third of the localities represented at a computed depth of 7000 ft. or less, and at two-thirds of the locations the depth to this temperature is 10,000 ft. or less. By extrapolation of the temperature curves for a few localities given in his table, he has computed that the critical temperature of water, 689° F., is reached at depths less than 30,000 ft. where temperatures of 212° F. are likely to occur at depths of 7000 ft. or less. Where a temperature of 212° F. is possible at 10,000 ft. or less, the critical temperature is with few exceptions reached at depths of less than 40,000 ft. In connection with an igneous mass at relatively shallow depths within the zone of circulating waters, evidence cited shows that volcanic carbon dioxide is added to the waters. Connate water or fossil sea water trapped with the sediments may contain carbon dioxide in free or combined state but in a relatively small quantity. Concentration of the gas in suitable traps is a necessary condition to accumulation of commercial supplies of carbon dioxide, as well as its separation from water by specific gravity.

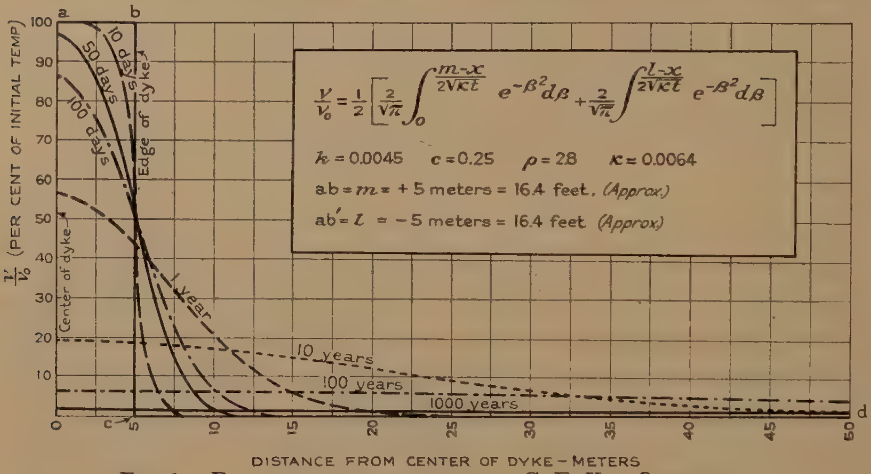

FIG. 1.—FLOW OF HEAT FROM DIKE, BY C. E. VAN ORSTRAND.

A curve (Fig. 1) showing the rate of flow of heat from a 32-ft. dike into adjacent rock of similar thermal conductivity at a temperature of 0° C. was calculated by C. E. Van Orstrand, of the Geological Survey. The mathematics of this curve is based on equation 25 by Ingersoll and Zobel.[18] The figures on the left side of the graph represent the percentage of the initial temperature of the dike, those at the bottom show the distance (in meters) from the center of the dike to which the heat penetrates the wall rock in a given time. It is evident that if the temperature of the intruded dike material is 1300° C. about 50 per cent of this temperature, or 650° C., would result at the contact immediately after intrusion; further, that at the end of one year following intrusion its heat would affect the rock 65 ft. from the edge of the dike, where a temperature of about 26° C. might be recorded. At the end of one year the flow of heat would not have affected strata 75 ft. or more distant from the edge of the dike. The curve is introduced to show the extreme slowness with which heat flows from a molten body and the improbability of heat from a dike causing any marked increase in temperature in the country rock sufficient to result in evolution of carbon dioxide contained therein, except in the immediate vicinity of the intruded mass. If the rocks adjacent to the dike are fused so as to close the voids, the emission of carbon dioxide and other gases from the magma would be retarded or prevented at least temporarily. The effect of such intrusions on a coal bed would result only in the evolution of volatile matter and the formation of coke. If the dike penetrates limestone or other limy beds the formation of carbon dioxide by reduction of carbonates might also be effected. The influence of the overburden on the formation of carbon dioxide is to be considered in this connection.

Commercial experience in the calcination of limestone, and the experimental data by Le Chatelier, reveal that the harder, denser and more crystalline the calcium carbonate is, the slower and more reluctantly will the carbon dioxide be evolved. The presence of silica or aluminum silicate accelerates the decomposition. Le Chatelier[22] gives the dissociation temperature of calcium carbonate as 812° C. at atmospheric pressure. As the pressure is increased the temperature required also increases and vice versa. Lovering (ref. 23, pp. 87–100) points out that:

> The rate at which heat will move from an arrested magma into the country rock adjoining it depends on (1) the initial temperature distribution; (2) the time elapsed after intrusion; (3) the specific heats, densities and thermal conductivities of the intrusive and of the country rock; (4) the presence of endothermic or exothermic reactions; (5) loss of heat through gaseous transfer; (6) the shape of the body.

From Lovering's curves (ref. 23, p. 99), his Plate 2, based on data from International Critical Tables, and from Ingersoll and Zobel, shown in

TABLE 3.—*Heat Imparted to Beds Immediately after Intrusion by Basalt Dike at* 1300° *C.* (2372° *F.*)

	K_1/K_2	θ_{ct}	Maximum Temperature Wall Rock	
			Centigrade	Fahrenheit
Coal	2.1229	0.68	884	1623
Shale	1.2666	0.55	715	1319
Limestone	0.7293	0.42	546	1015
Coral limestone	0.8755	0.47	611	1132
Gritty limestone	1.2500	0.57	741	1366
Oölitic limestone	0.8837	0.47	611	1132
Dolomite	0.7524	0.43	559	1038
Sandstone	0.7916	0.44	572	1062

his Table 1, the accompanying Table 3, giving the maximum temperature induced in beds of dissimilar composition, is computed for the special case of a dike at 1300° C. intruded in the strata listed. It is interesting to note the heat transfer that might result when a dike penetrates successive beds similar to those tabulated. The constant K is the ratio of the conductivity to the square root of the diffusivity. K_1 is the constant for the basalt and K_2 that for the rock penetrated. The ratio K_1/K_2 determines the temperature at the contact during the period immediately following intrusion. The symbol θ_{ct} represents the proportion or percentage of the initial difference in temperature between wall rock and intrusive, assuming the temperature of the wall rock to be zero.

If the temperature of dissociation of calcium carbonate is 812° C. or higher, depending on conditions, the table indicates that no carbon dioxide gas would be evolved from the lime rocks adjacent to the dike. With a sill, similar conditions may exist but the lava sheet probably has no bearing on commercial accumulations of carbon dioxide, as such gas formed by combustion of coal or organic matter would be lost to the atmosphere. Its effect, however, would be reflected by the temperatures of subsurface rocks within the limits indicated by the table. Experiments show that below 400° C. carbon dioxide is the principal gas evolved from rock material heated in vacuo. These temperatures, therefore, probably would be sufficient to expel occluded gases from the rocks affected. The rate of heat flow and distance from the intrusion are to be considered in this connection.

If this is a true interpretation of conditions in the geologic past, the indirect or thermal effect of volcanism on sedimentary deposits similar to those considered would result in little or no production of gas by chemical or physical change in the beds intruded. Nevertheless, the presence of steam in the magma might establish conditions favorable to generation of carbon dioxide from organic matter, or reduction of minerals.

Further evidence favoring an igneous source for carbon dioxide accumulations is furnished by the data computed by Allen (ref. 1, p. 29) for gases expelled from various types of igneous rocks measured at 100° C. and one atmosphere pressure. It was found that the gases from the average granite would occupy a volume 30 times as great as that of the rock from which they were expelled and the gases from the average basalt would amount to a volume 87 times that of the rock itself. If a corresponding emission of gas occurred in igneous intrusions generally, the resulting gas under pressure would find access to crevices and porous formations in proximity to such intrusions.

The critical temperature of carbon dioxide is about 88° F. and the critical pressure is 1070 lb. per sq. in. Unless a very low annual mean temperature and a pressure greater than 1070 lb. exist in a particular locality, it seems logical to conclude that carbon dioxide in commercial quantities exists as a gas in the pores of the reservoir except that portion absorbed by any water that may be present.

Favorable Areas

Available information indicates, therefore, that carbon dioxide accumulations of either organic or inorganic origin are possible, and available evidence favors the inorganic. In areas where it is of organic origin, the distribution, quantity and quality of source rocks would govern the size and extent of commercial accumulations in reservoir rocks in folds or geologic structures of similar effect, assuming that the physical principles governing its accumulation are the same as those governing hydrocarbons. The location in the geologic past of buried shore lines, inland seas, or lakes, is then an important factor in the selection of structures worthy of prospecting.

Carbonated springs, mud pots and some thermal springs or geyser areas representing the remnants of volcanic or subvolcanic activity are likewise areas to be considered as favorable for well locations. While such springs may be used directly, the drilling of wells nearby affords a means of avoiding the escape of free or dissolved gases to the atmosphere. At Saratoga Springs, N. Y., the wells are in basins near springs and the waters ascend partly under hydrostatic head. In thermal spring or mud-pot areas the accumulation or the supply of magmatic gases or liquids is governed more or less by proximity to the buried igneous mass. While the dome-shaped surface of a laccolith or the effect of intrusion of a volcanic neck or a dike may be similar to the folds in other regions, it may provide favorable conditions for accumulation under hydrostatic, volumetric, or capillary control as defined by Herold.[15] Sealed faults and lensing of the reservoir rocks may result in favorable conditions for accumulations also. Faulting, however, may produce suitable channels for migration of gases or liquids into porous formations.

The fact that carbon dioxide in commercial quantities occurs in anticlines or domes has been demonstrated by drilling. Whether these folds are the effect of deep-seated igneous intrusions, compressive forces, or differential settling of the sediments over an old land mass has not been determined. However, in one of the areas discussed, Wagon Mound, N. M., there is no doubt of igneous activity after the sediments were laid down, and unless the results of pre-Cambrian volcanism in the nature of geysers, hot springs, or submarine springs, were extant in the Cretaceous period or later, the pre-Cambrian igneous rocks could not have been the source of the gas. Fig. 2, showing the distribution of volcanic rocks in northeastern New Mexico, gives evidence favoring a causal relationship to the igneous activity of that region. The dikes, the extinct volcanoes and rather widespread distribution of extrusives in northeastern New Mexico certainly suggest, at least, that volcanism may have been an

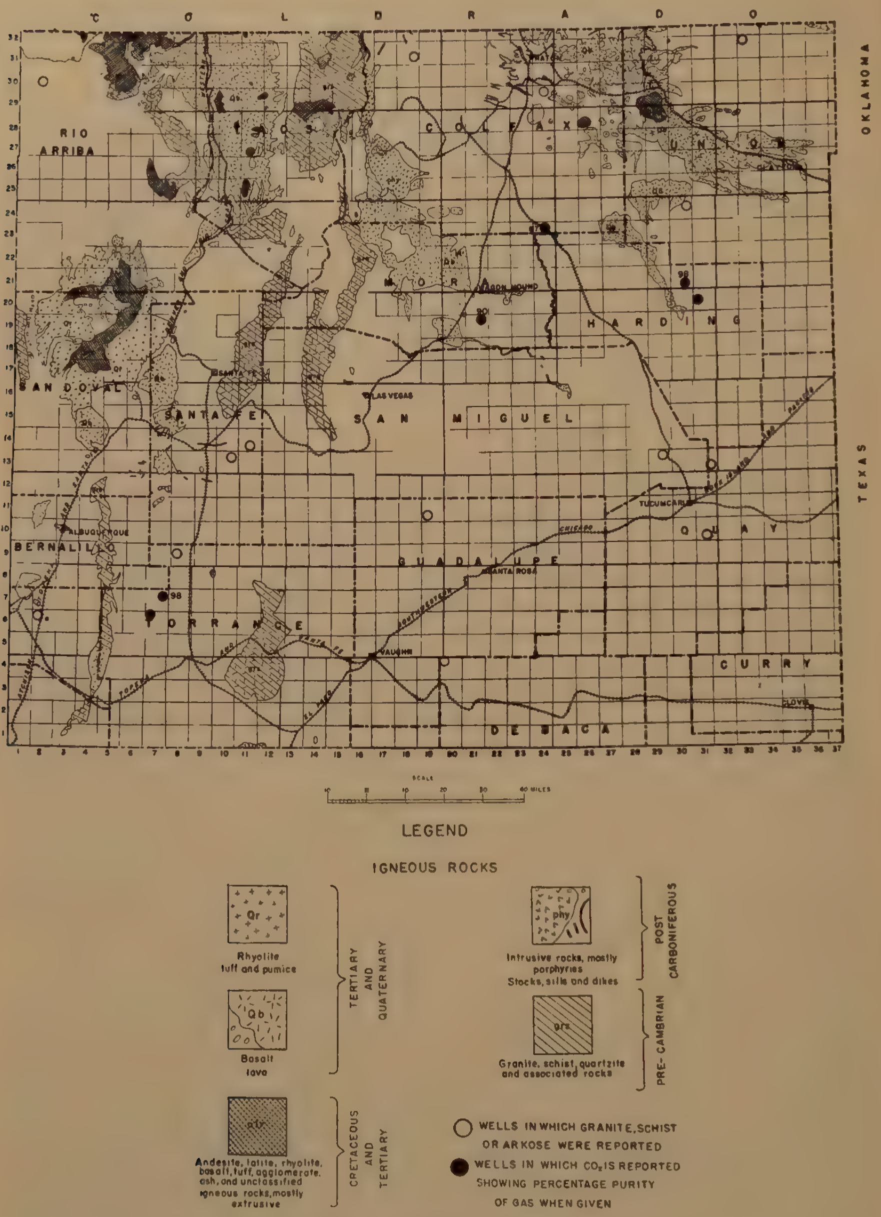

FIG. 2.—GEOLOGIC MAP, NORTHEASTERN NEW MEXICO.
Prepared from U. S. G. S. geologic map of New Mexico, by N. H. Darton and others.

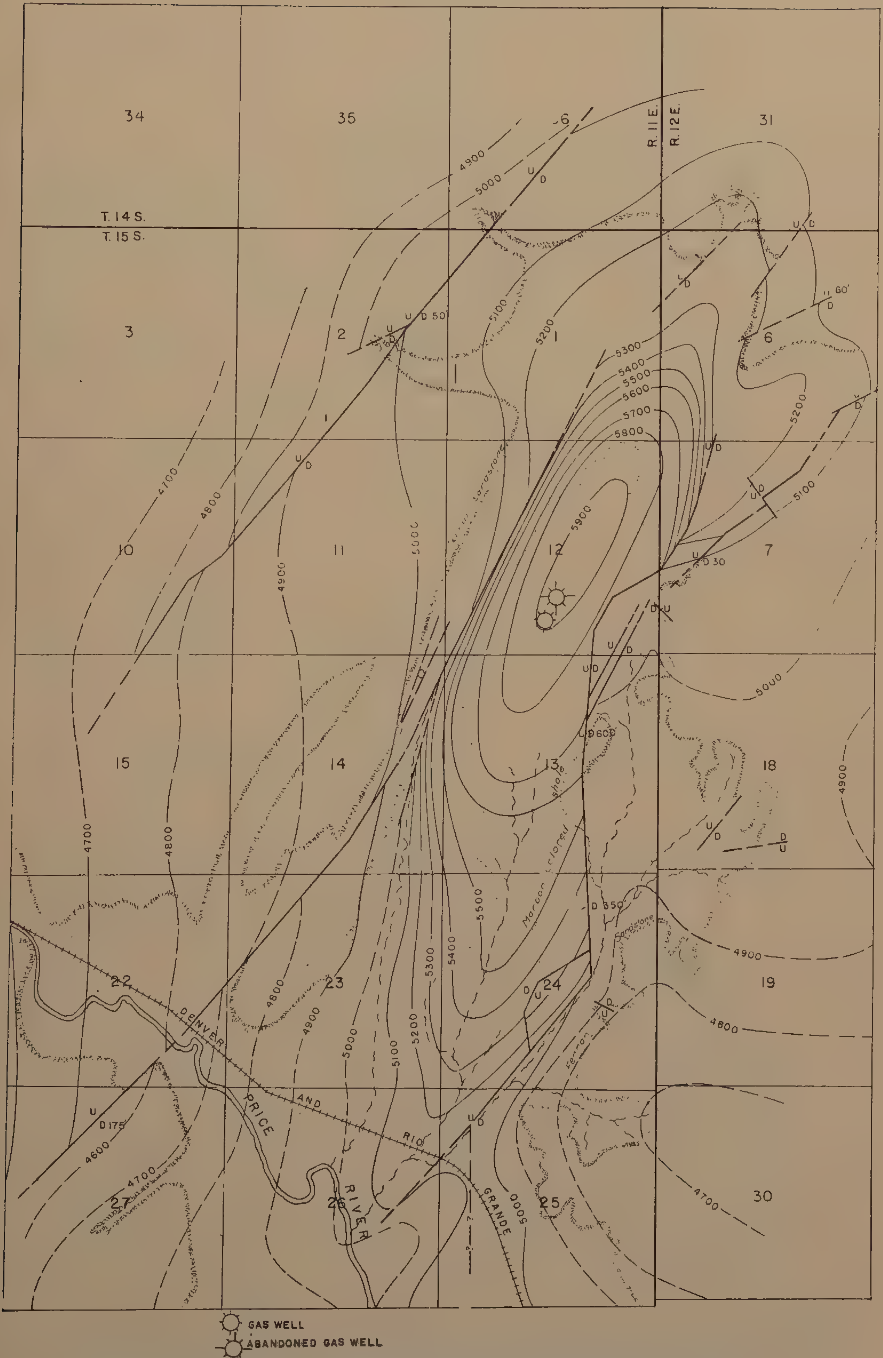

FIG. 3.—STRUCTURE CONTOUR MAP OF FARNHAM ANTICLINE, UTAH. By J. C. Miller assisted by R. S. Duce.

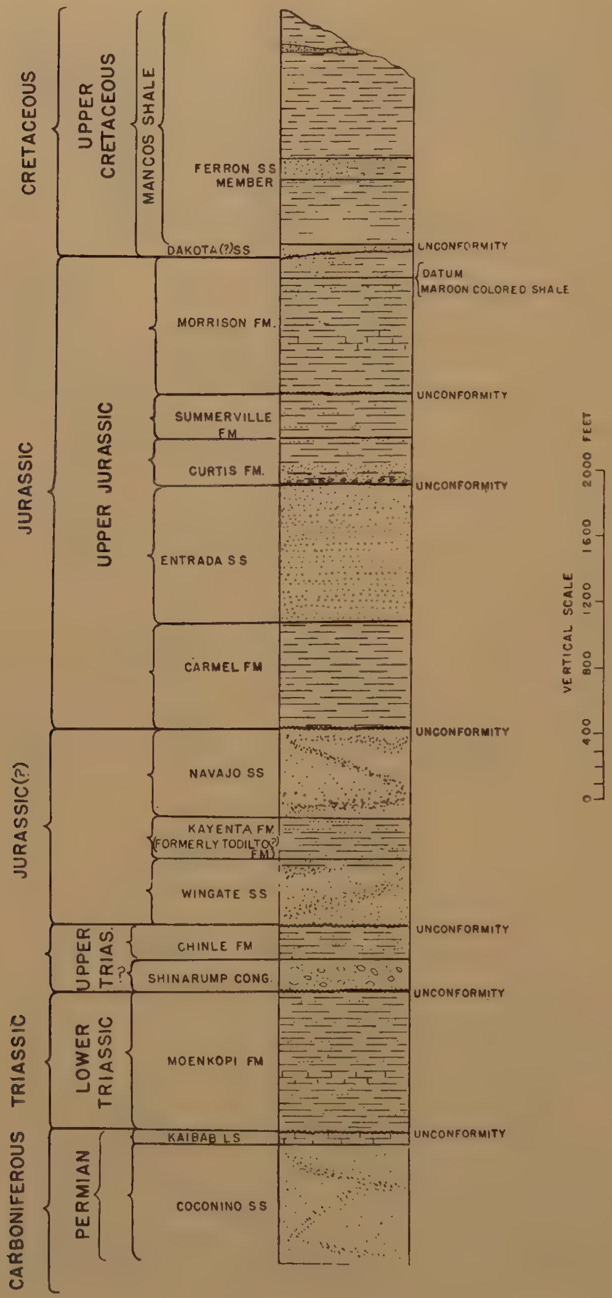

FIG. 3.—(*Continued*).
Generalized section modified from *Bull.* 806-C by James Gilluly.

important factor in supplying the gas either directly or indirectly in the scattered structures shown as productive of carbon dioxide gas.

Productive Geologic Structures

Carbon dioxide in appreciable amounts has been discovered in drilling a number of Rocky Mountain structures in the past but the gas was of no value to the operator or no thought was given to its utilization, therefore many of these wells were abandoned. Of the three areas discussed, the Wagon Mount anticline, New Mexico, is not developed. Both the Farnham anticline, Carbon County, Utah, and the Niland area, California, supply gas for the manufacture of liquid and solid carbon dioxide.

Farnham Anticline.—The Farnham anticline (Fig. 3) is about 140 miles southeast of Salt Lake City, north of the Denver & Rio Grande Western Railroad and the Price River, in Carbon County, Utah. Gas from a single productive well is piped to a 20-ton plant at Wellington, on the railroad, a distance of about 5 miles, where it is purified, liquefied, and converted into solid carbon dioxide, which is shipped to Salt Lake City and the West Coast. The gas analyzed by H. P. Cady, of the University of Kansas, was reported to contain 98 per cent carbon dioxide.

The geology of this area was described by Lupton[24] and Clark[8] and the structure was later mapped by geologists for the Midwest Refining Co. and by others. The first well was started in 1921, by the Utah Oil Refining Co., and was abandoned in 1924 at a depth of approximately 3235 ft. The second well was completed in 1930 by the Carbon Dioxide and Chemical Co. at a depth of 3115 ft. The productive sand is believed to be the upper part of the Coconino sandstone.

The anticline is a small fold on the north flank of the San Rafael swell. Its relation to regional structure has been well shown by Baker,[3] in a structure contour map of southeastern Utah.

The structure contours (Fig. 3) are drawn on a rather hard, fissile, maroon or purple shale near the top of the Morrison formation, about 200 ft. below the Dakota (?) sandstone. The Morrison formation crops out along the axis of the structure and sandstone beds believed to be of Dakota age dip steeply, adjacent to two faults on the east and west limbs, which roughly parallel the axis. Except for minor normal faults, the Ferron sandstone member of the Mancos shale forms a fairly continuous rim around the structure. The fault on the steep west flank of the structure appears to be of the scissor type, with a maximum throw near the south end of about 200 ft. The normal fault on the east flank also roughly paralleling the axis has a maximum throw of about 600 ft.

The relative location of the anticline with respect to igneous outcrops is shown on Fig. 4. Carbon dioxide has been encountered in wells in rather widely separated areas in southeastern Utah. No direct evidence was obtained to substantiate a statement that the gas in the Farnham

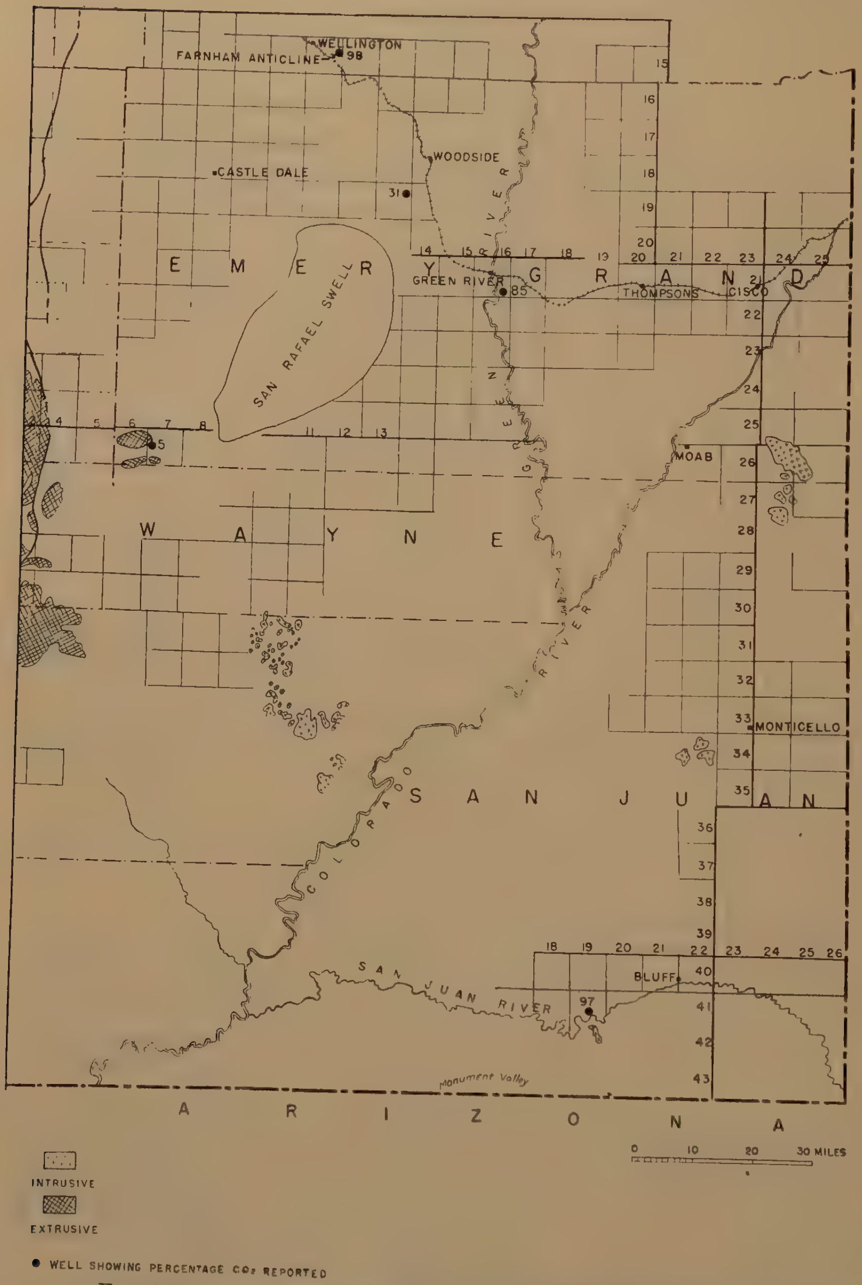

FIG. 4.—DISTRIBUTION OF VOLCANIC ROCKS, SOUTHEASTERN UTAH.
After reconnaissance geologic map of Utah by B. S. Butler (*Prof. Paper* No. 111).

anticline is of igneous origin; that source merely seems more adequate to account for the relatively large volumes of carbon dioxide, in addition to helium and nitrogen gases found in this portion of the state and adjoining parts of Colorado, by reason of the intrusive and extrusive rocks in and adjacent to San Rafael swell, also the LaSal, the Henry, and the Abajo Mountains. Numerous dikes are known in the Wasatch Plateau coal fields to the west. South of Price, Wellington, and Farnham, dikes are reported but were not verified by the writer. The strike faults on each side of the anticline might afford means of upward migration of magmatic gases. Nevertheless, the same channels would provide access to the sands or porous formations in the anticline for gases of organic origin.

Wagon Mound Anticline.—The Wagon Mound anticline, in Mora County, New Mexico, is about 8 miles south of the town of Wagon Mound, which is on the main line of the Atchison, Topeka & Santa Fe Railroad, between Raton and Las Vegas.

The first well on the structure was drilled by the Arkansas Fuel Oil Co. during 1925 and 1926 on the SE.¼ NE.¼ of sec. 11, T.19N., R.21E., to a depth of 2613 ft. This well presumably was drilled into the granite after passing through perhaps 400 ft. of arkose, which was logged as hard lime and sand. Non-flammable gas was reported at: 1160 to 1190 ft.; 1420 to 1425 ft.; 1670 to 1675 ft.; 1710 to 1800 ft.; 2220 to 2225 ft.

The upper sand may be tentatively correlated with the Santa Rosa sandstone in the lower part of the Dockum group of Triassic age; the sands between 1420 and 1800 ft. with those of the Manzano group of Permian age, including the Abo sandstone in the lower part; and the sandy lime reported between 2220 and 2225 ft. with the Magdalena group. However, Darton[11] considers the record of this well unreliable so that correlation of beds is hazardous.

During 1931 a well was drilled by the Fulton Petroleum Co. in the NE.¼ NE.¼ of sec. 14, T.19N., R.21E., to a depth of 1390 ft. The well is reported to have had an estimated capacity of 600,000 cu. ft. of gas that analyzed 90 per cent carbon dioxide, from a sand of doubtful Permian age between the depths of 1050 and 1135 ft. This gas was reported not to be commercial carbon dioxide gas because of contamination by hydrocarbon gas, and the well was abandoned.

The structure contour map (Fig. 5) resulting from reconnaissance work in 1935 indicates an anticline with the crest trending a little west of north. The Generalized Section shown on this plate was derived from U. S. G. S. Bull. 726-E, p. 176. The structure contours are drawn on a relatively massive sandstone correlated with the Dakota sandstone, Upper Cretaceous, and conform closely to the topography of the area. A remnant of what appeared to be a basalt dike in the SW. ¼ of sec. 2, T.19N., R.21E., extending northwest-southeast, was too poorly exposed to verify its extent or its effect on the sandstone beds. However, within a few miles and at the northwest side of the structure, Pliocene (?) and Pleistocene basaltic lavas cap the hills and extend into some of the valleys.

In this area, therefore, there is abundant evidence of igneous activity subsequent to deposition of the sediments, which contain sufficient lime to generate carbon dioxide gas by direct heat. Although the presence of organic source material is not eliminated, the areal map of northeastern New Mexico (Fig. 2) presents abundant visible evidence of volcanism. If this is considered in connection with the discovery of large volumes of carbon dioxide in a number of wells drilled in this part of the state, a

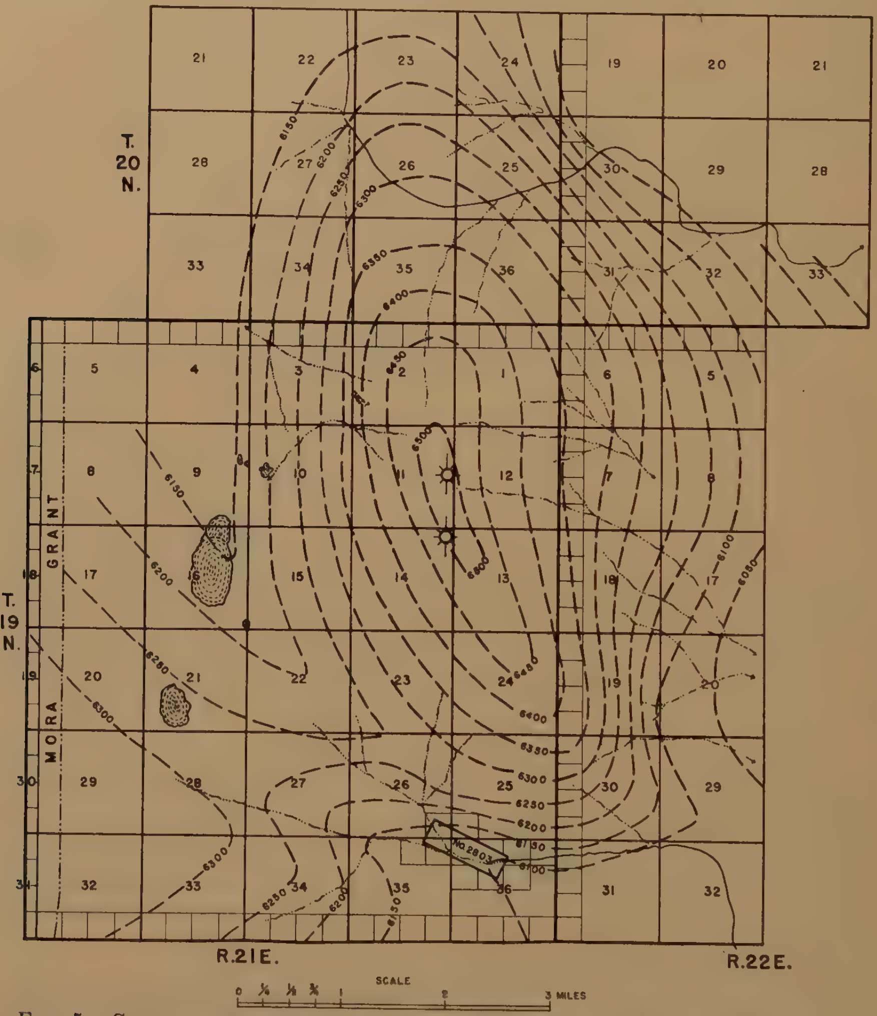

FIG. 5.—STRUCTURE CONTOUR MAP, WAGON MOUND ANTICLINE, NEW MEXICO. By J. C. Miller and Karl L. Walter.

conclusion that the gas is of igneous or thermal origin is favored, differing perhaps from the Farnham dome accumulation in that there may have been no extensive lateral migration of gas necessary to cause its concentration in favorable structures.

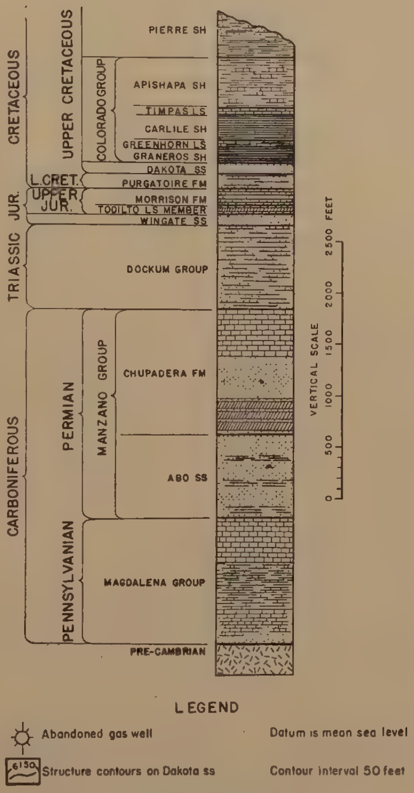

FIG. 5.—(*Continued*).

Niland Area.—The carbon dioxide developments in Imperial Valley, California, are close to the southeast end of Salton Sea, about 4 miles from the town of Niland, on the Southern Pacific Railroad. At present there are two plants in the vicinity manufacturing solid carbon dioxide from gas produced from wells and piped to the plants. This gas is reported 99 per cent pure.

The general geology and structure of the region is discussed by Brown,[6] who cited some of the early explorations by Williamson, Parke, Le Conte, Blake and others, also later investigations by Sykes, MacDougal, Harder, Fairbanks, Merrill and Mendenhall. Recently a good discussion of the structure was given in a geophysical paper by Soske and Kelly.[34]

Quaternary deposits immediately underlie the area, except three or four small buttes of obsidian and metamorphic rock protruding from the silts at the edge of the sea. The Quaternary deposits may be regarded as valley fill or lake beds consisting of sand, gravel and clay possibly 1200 ft. thick. The wells find the gas in these beds at depths of 500 to 700 ft. Some of the productive wells are within a mile of the mud volcanoes.

Owing to the character of surface beds, a determination of the structure is not possible except with the aid of geophysics. Soske and Kelly conclude that there is an igneous mass at relatively shallow depth. Its irregular but domelike shape may cause the accumulation of gas and the relatively large volumes of gas are probably primarily due to proximity to the igneous mass, although it is possible that carbon dioxide in the lake beds or similar deposits could be a contributing source at least. The lake beds, however, may act as a seal or impervious layer, preventing upward migration of the gases, which may not be indigenous with the sedimentary deposits. In view of the results of the Yellowstone Park investigation cited, the writer is inclined to agree with the conclusions of these authors that the gas trapped in the valley sediments of this area is of magmatic origin and that the location and arrangement of the buttes and mud volcanoes have a significant relation to the San Andreas fault, which is believed to extend along the east side of the Salton sink. The Salton Sea basin itself is considered by some writers to be a wedge-shaped graben.

ESTIMATION OF RESERVES

In fields or areas that derive carbon dioxide gas directly from springs, or from igneous sources in general, the quantity of gas ultimately available is indeterminate. Where the gas has accumulated in anticlinal folds or geologic structures that can be mapped with a sufficient degree of accuracy, an estimate of the gas reserves may be attempted. The basis for such estimates, however, involve a number of variable and often unknown factors—for example, temperature of the sand body and areal extent of the gas dissolved in any water present in the sand. There are few data available on reservoir conditions, the rate of depletion or decline, and the amount of recovery in carbon dioxide fields. Therefore, the accompanying figures are to be regarded as an approximation based on available experimental data applied to field conditions, and, in so far as these experiments simulated actual conditions in a gas well, this method of estimation is reliable. It is known that carbon dioxide deviates considerably from the laws of an ideal gas, particularly at very high pressures, and is very soluble in water, two factors of paramount importance in arriving at a fair estimate of future production. On the assumption that 50 per cent of the gas is recoverable when measured at a pressure of 10 oz. above an atmospheric pressure of 14.4 lb. per sq. in., the accompanying calculations are given for a field similar to the Farnham anticline before production started.

The following formula, from U. S. Bureau of Mines publications[16,19] modified to suit this special condition, was used in the preparation of the estimate:

$$Q = 43{,}560\, Ats \frac{(460 + 60)}{(460 + T_f)} \frac{(P_f d)}{14.4}$$

A = productive area, sq. ft.,
t = thickness of sand, ft.,
s = porosity of sand, expressed decimally,
P_f = absolute pressure in formation, lb. per sq. in.,
T_f = temperature in producing formation, deg. F.,
d = deviation factor at P_f and T_f (in this case the product of $P \times V$ as determined by Amagat).[37]

Instead of a pressure base of 14.4 lb. per sq. in., a pressure base of 10 oz. above this figure, or 15.025, was used. It is assumed that free gas exists between the 5700-ft. contour and apex of the structure (Fig. 3) and dissolved gas between the 5500 and 5700-ft. contours, aggregating areas of 25,176,809 and 18,773,489 sq. ft., respectively. A 20-ft. thickness of sand saturated with gas or water of which the effective porosity is 15 per cent is also assumed. The temperature in the sand at a depth of 3100 ft. is calculated to be 95° F. assuming a temperature gradient of 1° in 60 ft. A pressure on the sand or bottom-hole pressure of 882 lb. per sq. in. approximates the well-head pressure 750 lb. per sq. in. plus the weight of the gas. The factor *d* (taken from Amagat's data for $pv = 1$ at 0° C. and one atmosphere pressure) for 882 lb. per sq. in. and 95° F. is 0.7038, and for the conditions assumed this becomes 0.7967. In International Critical Tables (vol. III, p. 260), the values given for cubic centimeters of gas dissolved by 1 cu. cm. of water at a pressure of 60 atmospheres and temperature of 35° C. are 20.3 and 23.0. Sander[33] gives a value of 22.7 cu. cm. for a pressure of 60 kg. per sq. cm., and to simplify the calculation the higher value was used. Accordingly:

$$Q_1 = \frac{25{,}176{,}809 \times 20 \times 882 \times 0.7967 \times 0.15 \times 519.6}{15.025 \times 554.6}$$

$$= 3{,}309{,}491{,}543 \text{ cu. ft.}$$

$$Q_2 = 18{,}773{,}489 \times 20 \times 0.15 \times 23 \times \frac{14.696}{15.025} \times \frac{519.6}{554.6}$$

$$= 1{,}186{,}559{,}598 \text{ cu. ft. dissolved or in solution in water}$$

$$\frac{Q_1 + Q_2}{2} = 2{,}248{,}025{,}570 \text{ cu. ft.}$$

if a recovery factor of 50 per cent is assumed, which is intended to include allowance for abandonment pressure in excess of a pressure of 10 oz. above an atmospheric pressure of 14.4 lb. per sq. in. (The atmospheric pressure at the well was calculated to approximate 12 lb. per sq. in.)

The volume of gas Q_2, absorbed in the water is calculated from the values for solubility of carbon dioxide in fresh water and not salt water. However, it has been determined by McClendon[25] and others that:

> The change in P_H with change in CO_2 tension is affected only by the temperature . . . Changes in salinity theoretically affect the CO_2 tension and hence CO_2 content of sea water. Fox divides the CO_2 into two parts, one of which obeys Henry's Law and never exceeds 1 per cent of the total. It is this small fraction that is affected by salinity, but the changes in salinity ordinarily met with in the larger oceans change this fraction only about 1.5 percent, and the total change is exceedingly small. We have not been able to determine any effect of salinity on P_H or CO_2 content.

The possibility of diffusion of the gas in contact with the water in the absence of a barrier prohibiting indefinite migration away from points of concentration has been suggested.* This observation leads to speculation concerning the distance from the apex of a structure that such gas could diffuse in a porous medium before its concentration would be a negligible quantity commercially, eliminating the small fraction that would enter into combination with salts in the water.

If there is no water present in the sand, simply a case of volumetric control as defined by Herold,[15] the volume of gas in the reservoir should be of the magnitude of the free gas volume (Q_1) calculated. If the field is under hydraulic control, the boundary and quantity of dissolved gas on the slopes is continually changing as the free gas is withdrawn and the water encroaches. It is the saturated edgewater that furnishes the additional reserve (Q_2) as this volume of water subsequently advances up the slope. Such advances may be due in part to capillarity but in a sand body of great lateral extent, which probably outcrops on the mountains at a higher altitude, the advance of the water is primarily due to hydrostatic head; in other words, the reservoir is under hydraulic control in accordance with Herold's terminology.

The conditions postulated for this reservoir are therefore a fairly limitless sand body saturated with water, a finite quantity of gas, which may have originated from an igneous source in contact with that sand body, and eventual accumulation of the gas in the anticline.

If it is assumed that the anticline is a minor flexure in a sloping sandy body providing artesian conditions, the hydrostatic head would be greater in the adjacent syncline than on the anticline. If there is movement of water caused by a flow of water from the sand, the conditions may be similar to a long pipe line of which a portion is above the hydraulic gradient, in which event the head at the anticline would be a minus quantity, and there would be a tendency for gas to migrate and accumulate in such areas. It has been common practice, however, to estimate roughly the rock pressure of a gas sand by multiplying the depth by 0.4335; that is, to assume that the pressure is equivalent to the static head of water measured from the surface at that point. This would be about 1344 lb. per sq. in. on the sand at a depth of 3100 ft. in the Farnham anticline well. It is to be noted that a pressure of 882 lb. per sq. in. for the gas in the sand was calculated.

According to this hypothesis the hydrostatic pressure in the sand at the 5500-ft. contour would be in excess of 173 lb. per sq. in. greater than that pressure at the top of the structure. The same result is obtained if the hydrostatic pressure is calculated for the difference in head by reason of a sloping sand or porous strata in accordance with conditions similar to those cited for a pipe line. The apex of the structure, therefore, is a point of lesser hydrostatic pressure even before the reservoir is tapped by a well, and there is a tendency of gases and fluids to move toward such areas until the gas is in equilibrium with the hydrostatic head.

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* Oral communication by R. E. Stephens, of the U. S. Geol. Survey.

In a carbon dioxide gas-water system, diffusion of the gas, which varies with temperature and pressure, is perhaps an appreciable factor, and without a barrier such as a sealed fault or dike or increase of pressure on the edge of the gas reservoir or structure there is little to prevent diffusion of gas throughout the porous medium and its ultimate dissipation. If the temperature gradient is 1° per 60 ft. in depth, an increase of temperature of about 6° and an increase in hydrostatic pressure of 173 lb. at the 5500-ft. contour may result; in other words, an increase in temperature of about 7 per cent, and an increase in hydrostatic pressure of less than 20 per cent. The effect of an increase in temperature is more than compensated by the increase in pressure. In a closed system at approximately equal temperature throughout, the uncombined gas would migrate toward the center of the structure or point of reduced pressure, and not away from the apex; consequently, in addition to the separation effected by gravity, accumulation of gas in anticlines, domes and other suitable traps should follow.

Experimental data show that there is no marked change in viscosity of the gas between pressures of 0 and 60 atmospheres at temperatures between 20° and 40° C.; therefore this factor was omitted from the calculation. The resistance to flow would influence the rate of production and to a minor extent the ultimate recovery but until data are provided by additional experience refinement of the method of calculation seems unwarranted.

In the structure for which the estimate is made, the gas is assumed to be in contact with water, and its withdrawal is assumed to be compensated by evolution of the dissolved gas and encroachment of water until exhaustion of gas is accomplished. If all the water in a sand body of unlimited extent is saturated with the gas the problem is indeterminate and a case similar to that of volcanic springs.

CONCLUSION

The accumulation or concentration of natural carbon dioxide is dependent on one or more of the following factors: (1) proximity to volcanism, extinct or decadent; (2) suitable traps such as anticlines or domes, which are essential to its collection in geologic time; (3) springs or other conduits which provide a means of escape of free or dissolved gas. The recovery of the gas from such deposits may be effected by drilling wells on or near the critical points of these structures, but the number of these wells, whether they be gas wells or water wells, is limited by the rate of movement of the free or dissolved gas through the sand or porous formation and by the volume of available gas derived from the source rock. The location by a geologist of commercial deposits of this gas is, therefore, not a simple geologic problem and involves appreciation of the probabilities of unsuccessful drilling in areas where surface indications may be otherwise favorable.

Acknowledgments

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Factors of Composition and Porosity in Lead-zinc Replacements of Metamorphosed Limestone

By John S. Brown,* Member A.I.M.E.

(New York Meeting, February 1938)

As a part of a symposium on the relations of structure to ore deposition, in February 1938, the writer presented some tentative opinions derived from his experience with a number of important lead-zinc replacement deposits. These ideas were set forth, as a basis for discussion and a stimulus to further inquiry, in a mimeographed leaflet that read as follows:

> Intimate acquaintance with a number of lead and zinc deposits in metamorphosed limestones seems to indicate the existence of certain common features from which can be established some general principles governing the localization of ore in this type of formation. It is suspected that these principles can be applied, with modifications, to mineralization in unmetamorphosed limestone. In metamorphosed formations, some observed rules are as follows:
>
> 1. Bands or masses of pure limestone are very resistant to replacement by ore solutions, and are likely either to contain no ore or to resist replacement until near the end of mineralization. The reason for this apparently is physical, not chemical, since microscopic data indicate that when ore is deposited by far the greater part of it substitutes for carbonate. The chief factor is believed to be a lack of porosity in massive limestone that has undergone flowage and recrystallization.
> 2. Masses of intensely siliceous or silicated rock are likewise unfavorable ore receptacles. This seems to be accounted for by two factors: (*a*) chemical unsuitability or resistance to replacement, and (*b*) physical resistance to small-scale brecciation, which might facilitate the opening of effective channelways for solutions. Some low-grade ore may occur, however, and also sporadic fracture fillings.
> 3. The optimum condition for ore reception appears to be found in bands or areas containing carbonate and silicates (or quartz) intimately mingled in something like equal proportions. In this situation movement is likely to result in mixed flowage and fracture, producing a fine-textured porosity that admits solutions freely and provides access to an abundance of replaceable carbonate. Cleavage cracks in some minerals such as diopside are believed to facilitate the penetration of solutions.
> 4. Certain minerals or assemblages are regarded as favorable impurities in a limestone and others as unfavorable. Original quartz, and subsequently developed diopside, and perhaps garnet, are typical favorable pre-ore gangue; in general rather equidimensional, brittle minerals. Tremolite, biotite, and probably wollastonite, are typical unfavorable pre-ore gangue; in general highly elongated and somewhat flexible minerals likely to develop under strong shearing stresses.
> 5. Tentative opinion is that the ratio of lime and magnesia in a limestone is of little or no importance.

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> It is proposed to illustrate the foregoing principles by data from two typical deposits, the Aguilar lead-zinc mine in Argentina and the Balmat zinc-pyrite mine in New York.
>
> As applied to unmetamorphosed limestones the suggestion is that permeability is the chief factor. It may be supplied by bedding planes, brecciation from any cause, dolomitization in some cases, and doubtless by other means. Combinations such as bedding and brecciation are especially important. Lack of effectively dispersed channelways probably makes bedded limestones inhospitable to ore at many places.

Since that presentation, considerably more work has been done on the problem, resulting in some revision of the original impressions. The modified conclusions, with their supporting data, are set forth herein.

AGUILAR, ARGENTINA

The Aguilar lead-zinc mine (Fig. 1, *A*, *B* and *C*) is a substantial body of ore in the Province of Jujuy in northern Argentina, at an altitude of about 15,000 ft., on the eastern slope of the Andes. In summary, it is an instance of mineralization in a relatively thin series of limey beds, intercalated in a great mass of unfavorable shale and quartzite, which have been partly altered to hornfels. The whole assemblage is a typical product of "contact metamorphism."

In Fig. 1*A*, the areal geology and structure are shown in outline. There are two bodies of Tertiary granite, only one of which is important. That body is about 6 miles long and 2 miles wide. Several very large, nearly vertical, faults involve strata that consist of Tertiary and possibly Cretaceous beds resting unconformably on sediments in which the only positive fossils collected are identified as Ozarkian. This leads to the supposition that the rest of this series is Paleozoic, and the ore-bearing portion is regarded as Cambrian. The mineralization at the Aguilar mine, which is the principal deposit, is closely tied to the western margin of the granite intrusion and to the large fault that parallels it. As shown in the detailed section, Fig. 1*B*, the mineralization is restricted to three relatively thin members, which have been designated as beds 1, 2 and 3.

The general mineral sequence, pre-ore or gangue, comprises limestone beds containing considerable amounts of original impurities such as quartz and feldspar and minor zircon, metamorphosed by the intrusive with the production of large amounts of diopside and garnet and considerable rhodonite, some feldspar, and minor amounts of quartz, wollastonite, tremolite, biotite, muscovite, titanite, and so forth. The ore minerals in sequence, shown graphically in Fig. 1*C*, consist of small amounts of pyrite and pyrrhotite, a great deal of sphalerite and galena, and a trace of ruby silver.

Noteworthy is the gradation from very dark, iron-rich sphalerite in the beginning to a very light, iron-free character in the end. This is

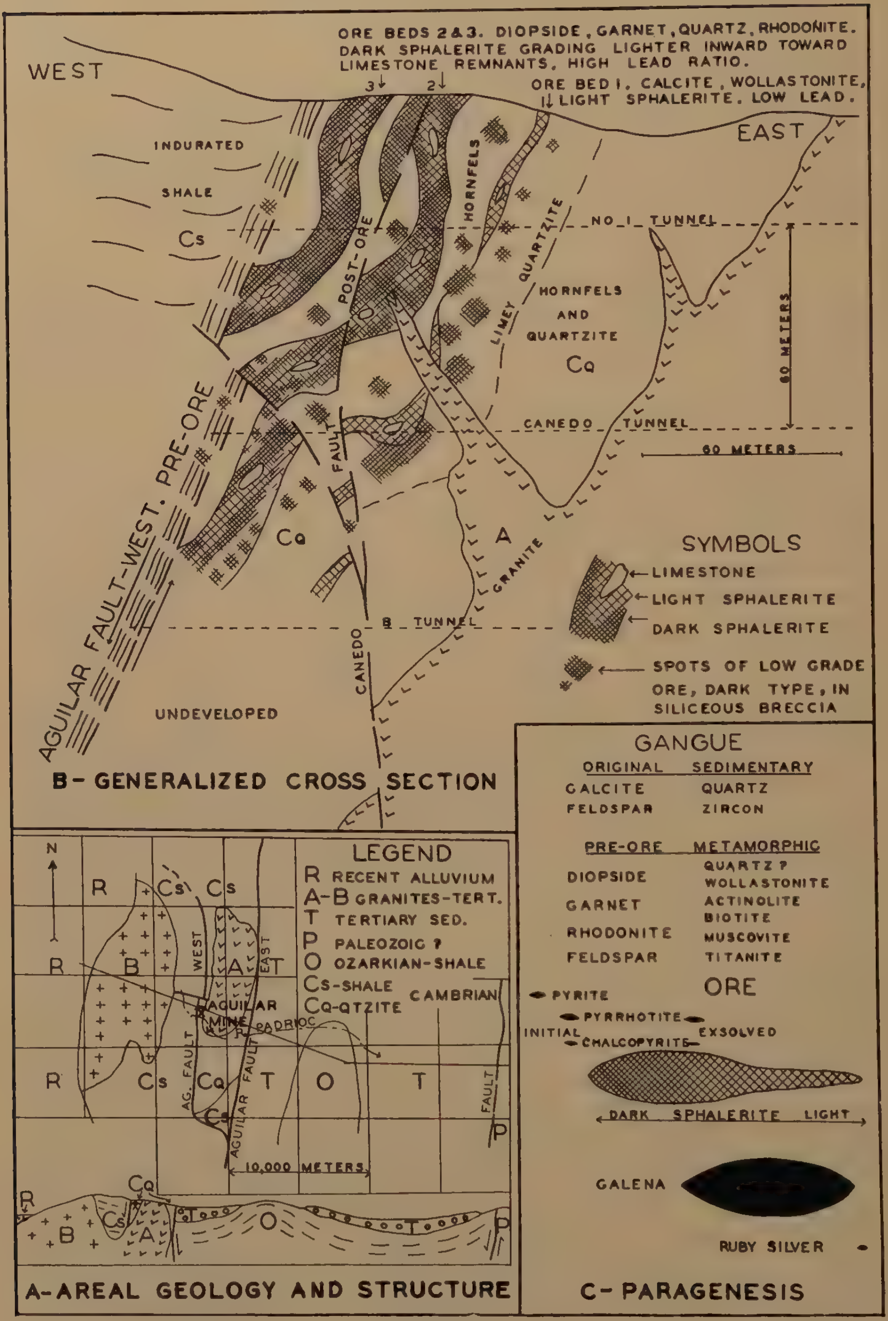

FIG. 1.—INTERPRETATION OF MINERAL RELATIONS AT THE AGUILAR MINE, ARGENTINA.

important because it gives a key to the paragenesis in this deposit. In beds 2 and 3, which had a great deal of the silicate minerals, sphalerite is most abundant marginal to the center of the limestone beds, and blocks of unreplaced limestone, with but little ore, may occur in the middle of the bands. Solutions did not attack the pure limestone as readily as they attacked the impure masses. Bed No. 1, which was thin but especially pure limestone, was replaced late in the sequence, nearly all by the light colored type of sphalerite. Right in contact with it, however, some exceedingly siliceous, limey quartzites contain low-grade ore, principally the early, dark colored type of sphalerite, showing that the solutions arrived early enough but could not easily replace the pure limestone.

Balmat, New York

Fig. 2 is a representation in plan and section of various ore shoots at the Balmat zinc-lead-pyrite mine. The several distinctive shoots, although connected here and there, are readily identified from level to level, *A*, *E*, *G*, etc. In section, certain ore bodies, such as *F* and *G*, section *X-Y*, show a close relation to controlling bands of unusual composition, ore body *F* to a hanging-wall rock high in mica and *G* to a similarly controlling band that is nearly pure tremolite. On the other hand, in section *A-B* the hanging wall is relatively pure limestone and the footwall is an intensely silicated limestone, and the ore lies between them.

In Fig. 3 are shown some graphic cross-sectional studies of drill holes through these various formations. These are diagrammatic representations of the chemical and mineralogical composition of ore and wall rock. Although not drawn to scale horizontally, the relations within each separate segment are volumetrically proportional. No. 24*B* is a drill hole through the ore body in which the hanging wall consists largely of pure limestone that is about 70 per cent acid-soluble carbonate. The remainder consists of insoluble silicates about equally divided between diopside and talc or serpentine. The ore contains very little unreplaced carbonate; only the small area at the top. It is composed of a great deal of pyrite, a considerable amount of sphalerite and a small amount of galena with a gangue chiefly of diopside, talc, and other noncarbonate minerals.

Allowing that the ore mainly replaced carbonate, but admitting that to some extent it may have replaced silicates, it will be seen that the pre-ore silicate content of the host rock was assuredly considerably higher than in the hanging wall. The footwall, on the other hand, consists of some 70 or 75 per cent of silicates, mainly diopside, a little talc, quartz and other minerals. This, therefore, was much higher in pre-ore silicates than the host rock. It contains only a small amount of carbonate and but little ore, mainly pyrite in visible fractures.

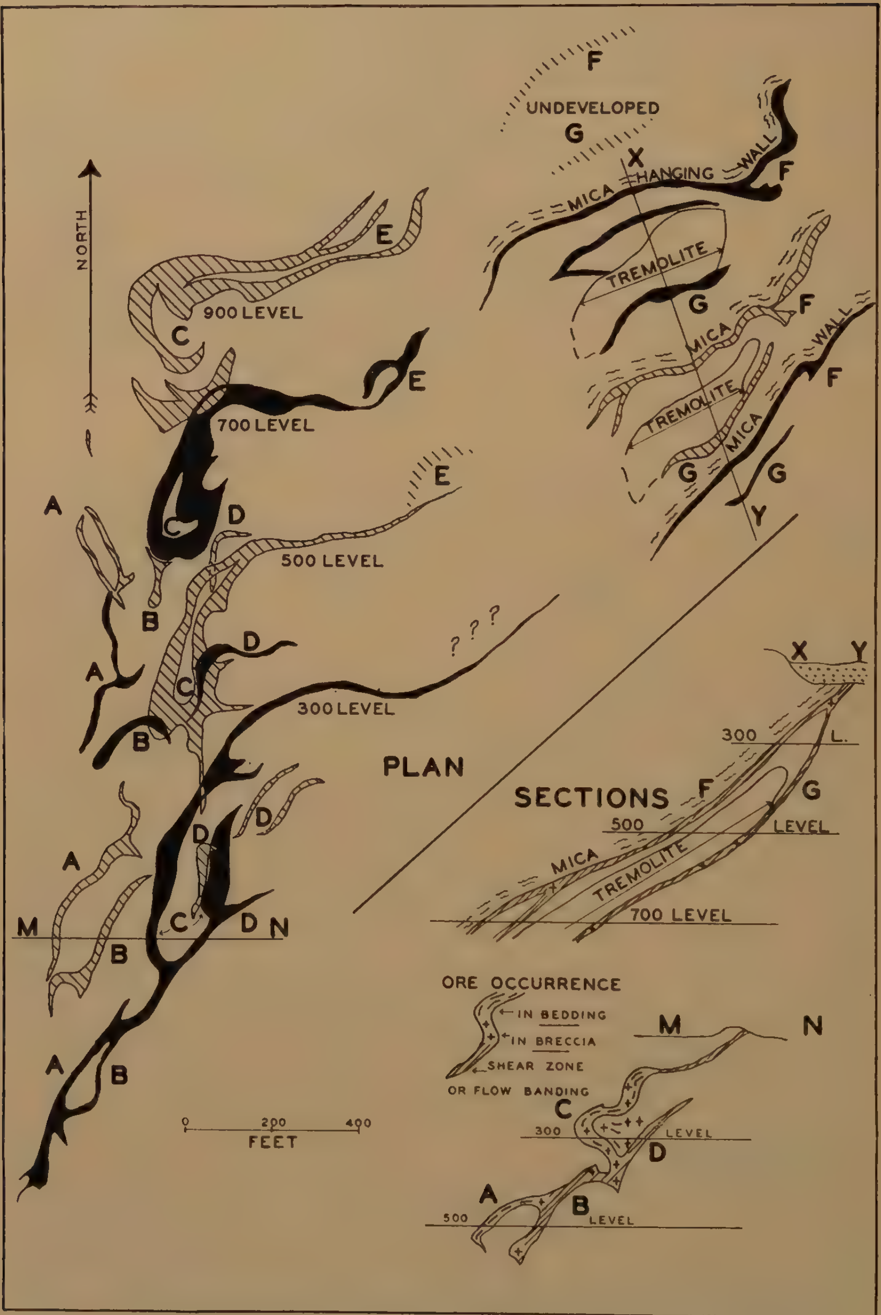

FIG. 2.—ORE SHOOTS IN PLAN AND SECTION, BALMAT, N. Y.

The second drill hole, 25*B*, across another part of the same area of the mine, shows 70 ft. of relatively pure limestone characterized by cleavage faces ¼ in. across, again with diopside, talc, and other minerals in smaller amounts. Here the ore has a particularly heavy content of sulphides, chiefly sphalerite with a little galena, which is slightly misleading. There is not the usual amount of gangue because of the presence of much secondary sphalerite, which was introduced later and replaced a large part of the gangue and of the pyrite. The footwall, again, is a highly silicated rock consisting of diopside, talc, quartz, phlogopite, and other minerals, with only about 10 per cent of carbonate. Ore formed along the transition between these two extremes.

The third section, No. 34*B*, shows differences not quite so large, with relatively purer limestone on both walls, about 50:50 silicate on one side, not quite so much on the other. The 11 ft. of ore contains about the same amounts of silicate as the more impure wall rock. Dropping down to the bottom, No. 57*B* is introduced to show that the pure limestone does not always occur in the hanging wall, but may as well be in the footwall. There are: 47 ft. of pure limestone that is 95 per cent soluble carbonate with very little silicate, 3 ft. of ore with still an abundance of carbonate, a considerable amount of pyrite and zinc ore, and a large amount of silicates. Over in the hanging wall is a highly silicated rock that contains considerable biotite. Finally, hole 90*B* illustrates the effect of tremolite, which is generally inhospitable to ore. The hanging-wall rock is nearly 95 per cent tremolite with a little carbonate. The footwall rock is strong in diopside, talc, quartz, and other silicate minerals. The ore is in a particularly brecciated strip between, and only in certain spots did this strip have enough carbonate available for replacement to make any appreciable effect.

The evidence for this mine, which could be multiplied over and over, is particularly clear that ore occurs in zones of intermediate impurity where the original host consisted roughly of about one-half carbonate and one-half silicates. The ore avoids the purer limestone on the one hand and the intensely silicated areas on the other, especially where the silicates possess high orientation, as in bands of mica and tremolite schist.

In contrast to Aguilar, the Balmat mine is an instance of mineralization in a wide area of limestone of deep-seated metamorphic character, in which are intercalated minor bands of intensely silicated and impure material.

Conditions at the Edwards zinc mine, 12 miles from Balmat, are in most respects very similar to those at Balmat. These will not be treated in detail, although that mine also has contributed largely to the writer's experience.[1]

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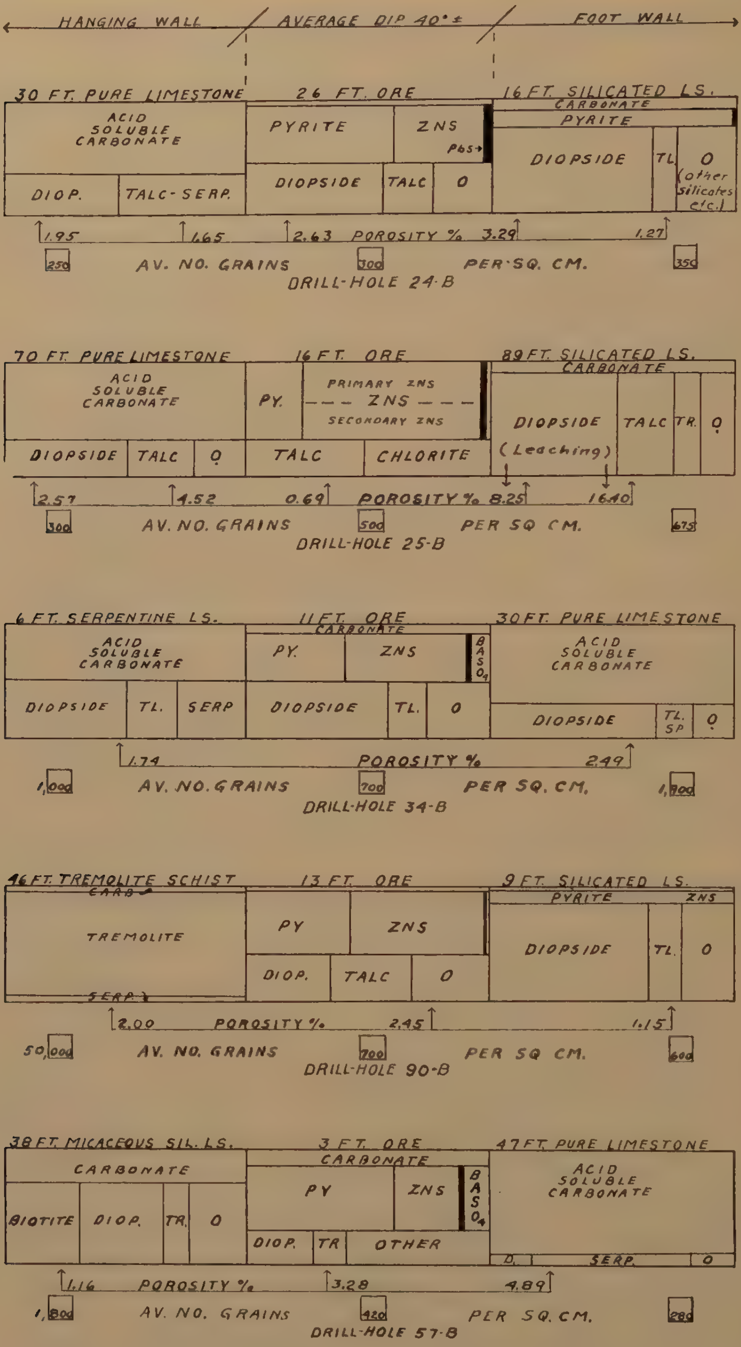
[1] References are at the end of the paper.



NOTE: ALL PERCENTAGES AND AREAS ARE VOLUMETRIC

FIG. 3.—CHEMICAL AND PHYSICAL DATA ON MINERALIZATION AT BALMAT, N. Y.

Tetreault, Quebec

An additional important example of the type of deposit under discussion is afforded by the Tetreault mine, situated near Notre Dame des Anges, about 150 miles northeast of Montreal, P. Q. This has produced more than a million tons of massive lead-zinc sulphide ore, in addition to a substantial amount of ore of lower grade. Through the courtesy of Dr. J. L. A. Tetreault, owner of the mine, the writer was privileged to spend two days in an examination of that property in 1938, under the excellent guidance of Dr. F. F. Osborne, who was making a geological study of the deposit for the Quebec Bureau of Mines.[2]

The general geology is fundamentally similar to that of the Edwards-Balmat district, New York. Pre-Cambrian sedimentary rocks, chiefly paragneisses of the Grenville series, are cut by ancient gabbro-amphibolites, and by later but likewise pre-Cambrian granite. The ore deposit occurs in a calcareous band intercalated in the gneisses, associated with local peculiarities of folding and shearing. Mineralization in any important amount is restricted to a band about 1 mile long and generally not more than 100 ft. wide. Commercial production has been confined to a length of 1500 ft. and a depth of about 400 ft., below which the favorable carbonate band at least temporarily fails. Two published descriptions deal in some detail with this mining operation, one by Bancroft[3] written early in the development of the deposit and a description by the Staff of British Metal Corporation,[4] which operated the mine in its most productive period. Fig. 4 is redrawn from the latter article, the chief point being that it shows that considerable masses of nearly pure tremolite constitute an important element of the gangue, bearing out in some degree the general inhospitality of tremolite as a host rock, an inference subject in this case to certain modifications noted hereafter.

Bancroft's description of the mineralization is in part as follows (p. 126):

> In general, the limestone has lost all semblance of its original character, since it has been changed *chiefly into tremolite* together with diopside, phlogopite, biotite, actinolite, scapolite, wilsonite, anorthite, apatite, epidote, garnet, titanite, quartz and recrystallized calcite, and dolomite; a little chlorite and talc have been developed locally, because of the alteration of the micas. This band is irregularly mineralized with zinc blende, galena and pyrrhotite, and a few scattered grains of pyrite and chalcopyrite; in some places, small crystals of arsenopyrite and a few small flakes of molybdenite and of graphite have also been found.

The reference to tremolite has been italicized in quoting, since it is almost certainly more important in volume than all the other silicates mentioned. Actually it is not all tremolite, but grades into actinolitic types and even at some places is supplanted by gedrite, according to Dr. Osborne.

The writer's inspection of this ore deposit was made at a much later stage in its exploitation, and the study of a set of thin sections suggests the following generalizations.

Tremolite (including actinolite) is the all-important gangue mineral, probably constituting something like half the total gangue in the ore as mined. Its distribution in the altered calcareous band is variable, so that in places the rock is almost entirely tremolite, but there are all gradations through partially silicated rock into unsilicated or differently altered phases with very little tremolite. The tremolite usually shows some degree of parallel orientation, but quite imperfect, and may be rather diversely oriented through the altered rock. These features of diverse orientation, a tendency to dissemination, and considerably coarser texture, differ from the situation at Balmat, where much tremolite is concentrated in very fine-grained masses of great purity and highly perfect schistosity, and these masses are very resistant to mineralization.

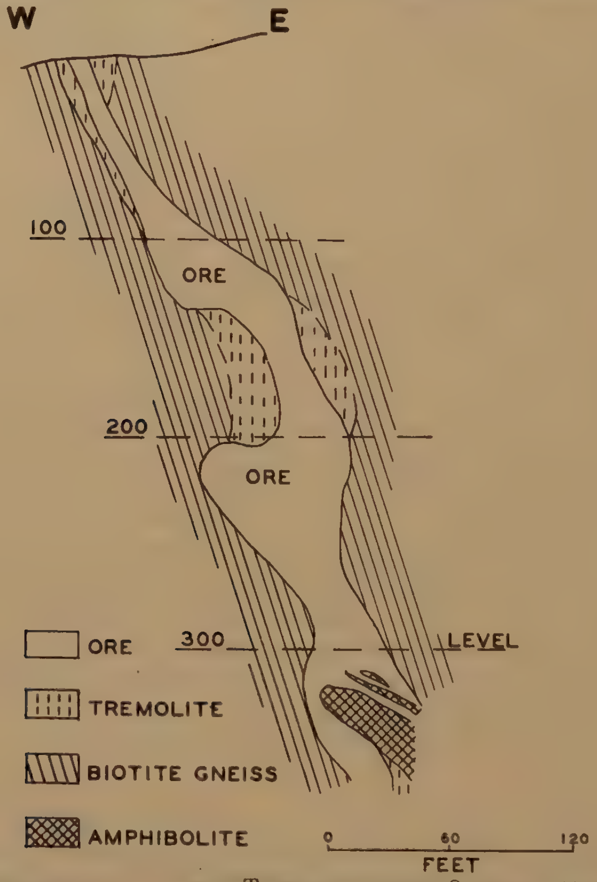


Fig. 4.—Mineralization at the Tetreault mine, Quebec. (After British Metal Corporation.[4])

The remaining gangue comprises smaller but important amounts of carbonate, diopside, phlogopite and other micas, plagioclase and quartz, all of which may be concentrated into bands or areas without much tremolite but often are associated with highly tremolitic rock.

As at Aguilar and Balmat, sulphides were deposited chiefly as a replacement of carbonate, the attack in some cases being sufficient to replace all the carbonate and even a minor portion of the silicates. An important fraction of the ore mined occurred as nests and bands in the highly silicated tremolitic masses and was deposited in and along actual fracture zones, which, according to Dr. Osborne, had been filled with secondary carbonate, which the ore replaced. Specimens from several of the richest and most productive stopes, however, strongly indicate a preference of good ore for rocks of intermediate silication with originally a substantial amount of disseminated carbonate. On the other hand, a well defined band of nearly pure limestone near the footwall, south of the shaft, on the second level is several feet thick and contains no ore. Minor streaks of ore occur below this member and a major stope above it. An analysis of the rock shows it to be 56.6 per cent $CaCO_3$, 37.87 per cent $MgCO_3$, with 5 per cent impurities, chiefly tremolite. As elsewhere, this confirms the general observation that pure limestone is often if not always inhospitable to ore.

Review of Literature

One of the most interesting papers bearing on this subject is by Umpleby,[5] entitled "The Occurrence of Ore on the Limestone Side of Garnet Zones." He cites seven districts in the western United States and Mexico in which the rule seems to apply to deposits of the class then generally discussed as "contact metamorphic in limestone." Umpleby's title seems to be another way of stating the substance of points 1, 2 and 3 of the writer's original summary; namely, that ore is found in neither very pure nor intensely silicated limestone, but between these in zones of intermediate silication.

As against this conclusion, it is only fair to cite a recent article by V. C. Kelley[6] on the Darwin deposits, California, which concludes that the Umpleby rule is inapplicable in that place, "for the silicate rocks in most cases extend far beyond ore bodies at the contact" (p. 1007). However, it seems probable that this may be due in large measure to the common occurrence of the Darwin ore bodies in definite fissures and fracture zones rather than as strict replacements.

Dolomitization

The significance of dolomitization as a factor in the localization of ore, or as a guide to its occurrence, has received considerable attention. In a notable review of the subject of dolomitization and ore deposition, Hewett[7] finds no clear-cut generalization possible. Ore may occur in dolomitized or in undolomitized limestone, and dolomitization, although usually earlier than ore deposition, may or may not be related to it genetically. Where it is so related it is sometimes a useful guide to exploration.

Foshag[8] quotes several analyses of the limestones in the Los Lamentos district, Mexico, and concludes: "Obviously the slight differences between the limestones are hardly sufficient to appreciably affect the emplacement of a very large ore pipe." He attributes the control to porosity, dependent on original character and later brecciation. This, it should be noted, is in relatively unmetamorphosed limestone.

Hayward and Triplett[9] likewise present extensive data for the Mexican deposits of the type common in unmetamorphosed limestone, without establishing any convincing relation between the dolomite content and ore, but with considerable suggestion of a physical control.

These results are quite in harmony with the writer's own experience as regards metamorphic limestone. At Balmat the carbonate gangue and waste, according to a number of analyses, is essentially dolomite, both in the ore and the wall rock. At the Edwards mine it is chiefly dolomite but may be essentially calcite in places. At Aguilar it is probably chiefly calcite. At Tetreault it would appear to be chiefly dolomite. Dolomitization where present at these places is believed to have preceded ore deposition and to have had little relation to it.

POROSITY

Bain,[10] in a stimulating article based on original experimentation and observation, has raised some pertinent questions as to the physical and chemical control of metasomatic replacement, his data having been obtained chiefly in marble quarries, where local mild silication and feeble sulphide mineralization are common. His essential conclusions applicable to ore deposits seem to be:

1. That sulphide mineralization avoids the silicated areas (these areas have low porosity, which may or may not be a factor).

2. That its end effect is to reduce the porosity of its own host below that of the adjacent unmineralized limestone (if, indeed, it may not have preferentially selected limestone of lower porosity in the beginning):

> A second singular feature of metasomatic deposits is partiality to formations or parts of formations possessing exceedingly low porosity. Quartzites are more subject to metasomatic replacement than sandstones, and crystalline limestones are replaced more often than very porous limestones; . . . Limitation of metasomatism to rocks of low porosity suggests that capillary rather than large pores, play an important part in causing solution of the solid phase of the system.

(That is, solution of the rock replaced.)

These conclusions are considerably at variance with the writer's assumptions regarding porosity at the time this study was initiated and as it was tentatively outlined in the summary (where the field evidence that major ore bodies seem to prefer areas of intermediate silication is interpreted to mean that these areas are, therefore, most porous, or permeable).

In order to provide some factual basis for a choice of conclusions, arrangements were made with Professor Bain for porosity determinations on a number of selected specimens from the drill cores delineated in Fig. 3, and grateful acknowledgment is due him, both for these determinations and for a critical reading of this discussion.

Porosity determinations were made at the points indicated by the arrows in Fig. 3, on pieces of core averaging 2½ in. in length and either of *E* size (about ¾-in. dia.) or "A" size (about 1$\frac{1}{16}$ in.). The method used was that of gas absorption. Bain states that although porosities undoubtedly have been increased by the mechanics of drilling, the values probably have not been distorted out of their relative magnitudes.

The grains per square centimeter shown in Fig. 3 were determined in each case from several thin sections, and represent essentially only primary gangue or ore minerals; that is, carbonate, diopside, tremolite, quartz, mica, and sphalerite, pyrite, galena, barite. The fine aggregates of talc and serpentine were assigned to the grains they replaced, usually of carbonate or diopside. Since talc and serpentine are believed to be mainly later than the ore, the grain counts should represent the rock at the time of ore deposition. Unquestionably the formation of talc and serpentine have somewhat modified the original porosities, but these effects seem to have been reasonably equal in ore and wall rock.

Drill Hole 24*B*.—At drill hole 24*B*, the differences in porosity do not seem very significant, especially considering that the grain counts are also rather uniform, indicating that capillary openings are of the same general size. This suggests that the controlling factor may have been merely the admixture of silicates and carbonate in favorable proportions, which might be an electrochemical effect.[11]

Drill Hole 25*B*.—The exceedingly low porosity of ore at drill hole 25*B* is almost certainly the result of sealing secondary deposition of sphalerite (and chlorite) from solutions believed to have been supergene.[12] This suggests that cold and dilute ore solutions are effective at porosities much lower, and in openings much smaller than in primary, high-temperature replacement. The excessive porosity of the silicated footwall rock is puzzling. Bain observes that it may be due to the presence of microscopic geodal cavities, but the writer is more inclined to believe it a feature of the excessive talc and phlogopite alteration that is shown by thin sections of these particular specimens. The talc is reasonably certainly post-ore; the phlogopite may or may not be. The high porosity seems to imply hydrothermal leaching.

Drill Hole 34*B*.—No ore was available at drill hole 34*B* for a porosity test, and the results on wall rock are not illuminating. Some supergene leaching in this locality adds to the uncertainty.

Drill Hole 90*B*.—Results definitely suggest that the ore zone at drill hole 90*B* was porous and was characterized by favorable openings, larger than in either wall rock. The excessive grain count in the hanging wall, with moderate porosity, points to exceptionally small and unfavorable openings there.

Drill Hole 57*B*.—The section at drill hole 57*B* is particularly illuminating, and the possibility of supergene leaching seems definitely ruled out (700-ft. level, no water courses near). The footwall consists of almost pure limestone; it has high porosity and low grain count, hence large openings, and therefore is exceptionally porous, but it contains no ore. The hanging wall has low porosity and high grain count; hence very fine openings. Ore deposition took place at the contact where conditions were intermediate as to porosity, grain count and size of openings, and where the rock was a more equal mixture of carbonate and silicates. Was it due to the size of openings or to an electromotive stimulus?

Conclusions

The results of further study have modified in important respects the conclusions tentatively set forth, mainly as a basis for discussion, in the original presentation of this subject. In general, it is thought that the field observations are sound, but the deductions set forth in their explanation, based on the field geologist's common interpretation that replacement by ore solutions depends on "permeability," are dubious. Thus point by point:

1. It seems true that pure limestone is generally resistant to ore replacement; but the reason is not necessarily porosity. The unreplaced pure limestone may be more porous than the impure rock that is replaced.
2. It still seems true that intensely silicated rock is unfavorable; that perhaps chemical unsuitability is one factor; but lack of porosity probably is not a factor of much importance, although the small size of openings may be at some places.
3. The favored condition for ore deposition seems to be in rocks that combine silicates and carbonate in an intimate mixture of roughly equal proportions; but the reason is not established as actual porosity. It may have some relation to size of pore spaces, capillaries of intermediate size apparently being favored by the magmatic solutions generally involved in this discussion; but it may be chiefly a matter of electric potentials between silicates and carbonate, or, as deposition progresses, between sulphides and carbonate.
4. Point four probably has considerable validity as a matter of observation; but it seems likely that it is not so much that certain minerals

are unfavorable impurities as that they tend to occur in forms that yield openings of an unfavorable character, either too small or too large.

5. No reason has been found to change the conclusion that the lime-magnesia ratio is of little importance.

6. An added feature is the suggestion that temperature and concentration are important factors in relation to the size of openings, and that with low temperature, or at least with dilute solutions, metasomatic processes tend increasingly to favor openings of smaller size.

7. Not to be ignored is the possibility that in some deposits post-ore solutions, either deep-seated or superficial, may have so modified the porosities existing at the time of ore deposition as to vitiate the significance of porosity determinations. In all such studies this feature of the paragenetic sequence should be weighed carefully. The subject is believed to merit much further investigation.

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Newly Recognized Features of Mineral Paragenesis at Leadville, Colorado

By Edward P. Chapman,* Member A.I.M.E.

(New York Meeting, February 1939)

In the Leadville district toward the close of the "intermediate mesothermal period" of mineralization, there occurred a stage of ore deposition marked by a rather complex mineral association. As bismuth minerals formed in many places during this period, it is here called the "bismuth stage" for convenience of description. The minerals so far identified with this stage, listed roughly in the order of prominence, are: chalcopyrite; several varieties of galena, differing slightly from one another in their small contents of silver, bismuth and tellurium; altaite; hessite; galenobismutite; alaskaite; aikinite; gold; tennantite; argentite; and perhaps sphalerite and arsenopyrite. With the exception of gold, the age relations of these minerals are difficult to determine. As shown in their descriptions, they all appear contemporaneous and hypogene. Gold may be in part contemporaneous, but most of it is distinctly later.

Where minerals of this stage occur so that they can be mined alone, as at the Tucson mine, they constitute high-grade ore. Elsewhere their presence in small amounts has served to increase greatly the value of what otherwise would be low-grade pyritic or zinc-lead sulphide ore.

The distribution of the bismuth ores corresponds closely to the distribution of gold ores, though not so general. It seems probable that most of the gold in the district was deposited during the "bismuth stage." These ores occur relatively near the supposed centers of mineralization in Breece and Printer Boy Hills or deep down along the Tucson-Maid fault, which is one of the well recognized channels of mineralization in the Iron Hill and Graham Park areas. Consideration of the high-grade nature of this mineralization and the fact that it appears to be found relatively close to the source of mineralization suggests that prospecting along some of the known channels, even deeper than they have yet been prospected, may offer hope of commercial success.

INTRODUCTION

The Leadville district has been studied since 1880, and numerous detailed geologic descriptions of it are available in print; so also are more or less complete summaries of the mineral paragenesis, representing what was known at various periods up to 1927, the year of publication of *Professional Paper* 148.[4] The writer has been engaged as consulting geologist at Leadville since the year 1926, and has been able to examine various types of Leadville ores throughout this period. Inasmuch as

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* Consulting Engineer.

[4] References are at the end of the paper.

several features of these ores have not been described, and as many of the mines in which they occur are no longer accessible, it seems appropriate to give brief descriptions of the unusual minerals observed and of their paragenetic relations. For convenience the treatment may better be regional than topical.

OUTLINE OF MINERAL PARAGENESIS

The paragenesis of the minerals contained in the ore bodies of the Leadville district is particularly well presented in a paper by Loughlin and Behre[5] and by Emmons, Irving and Loughlin in *Professional Paper* 148.[4] Ignoring the hypothermal minerals, which are of little economic importance and will not be considered in this paper, both the inner and outer parts of the district are characterized by minerals commonly assigned to the mesothermal group, although some are assigned to the epithermal and telethermal groups. The minerals of the inner or main part of the district include (1) manganosiderite, which is characteristic of the early or hotter mesothermal minerals; (2) quartz, which is characteristic of the intermediate mesothermal minerals, although large masses of jasperoid found in the outer parts of the district may indicate cool mesothermal or even telethermal conditions; (3) common sulphides, which are characteristic of intermediate mesothermal conditions, although galena and zinc blende with a low content of iron are also characteristic of cooler mesothermal conditions in the outer parts of the district. Deposits in the outlying parts of the district are characterized by a gangue of barite and quartz and in the most remote areas by dolomite and other carbonates.

In general four stages of sulphide deposition have been recognized: (1) pyrite, (2) zinc blende, (3) galena, and (4) bismuth and related minerals. Chalcopyrite occurs in the last three stages and in consequence is an unsatisfactory indicator of any particular stage. Reversals and overlapping of these various stages are not uncommon.

These two paragraphs summarize the previously recognized and described features of mineral paragenesis in the Leadville district. The writer has found little that is new regarding the first three stages, but newly available material containing minerals of the fourth stage has added several features of interest. In consequence this paper deals largely with the distribution and mineralogy of this stage, which for convenience of description is here designated the "bismuth stage."

DISTRIBUTION OF MINERALS OF BISMUTH STAGE

Although the minerals of the "bismuth stage" occur in relatively minor amounts, they often contain precious metals of economic importance, so that the ore bodies containing them are greatly enhanced in value. Bismuth minerals have been found most prominently in the ore bodies on Breece Hill (Fig. 1), which is the location of the Breece Hill stock, the supposed center of mineralization. Here, however, the bismuth occurs largely in the oxidized zone and there is no opportunity to study the occurrence of the original bismuth minerals in place; but a few specimens that contain bismuth sulphides, marked as having come from Breece Hill, have been borrowed for study from the mineral collections of others; one definitely came from the Garbutt mine. These specimens contain the same minerals in the same association as specimens studied from elsewhere in the camp, and it is probable that all the bismuth on Breece Hill was deposited in this "bismuth stage" of mineralization.

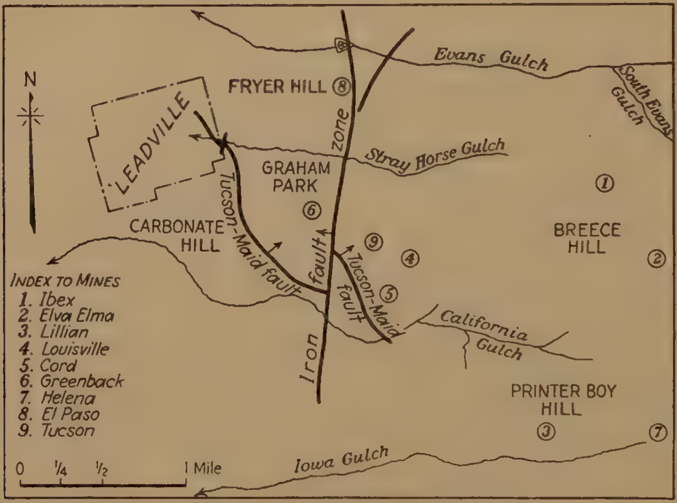

FIG. 1.—SKETCH MAP OF LEADVILLE DISTRICT.

Bismuth has also been prominent in the ores from the Lillian mine on the Iowa Gulch side of Printer Boy Hill, about 1¼ miles south of Breece Hill. Here the minerals occur close to what is commonly considered a secondary source of mineralization (ref. 5, p. 224). The specimen from this occurrence that has been available to the writer shows no evidence of a distinct stage of mineralization, although the bismuth mineral is later than pyrite.

Bismuth has also been reported from the deeper workings of the Cord and Whitecap winzes and the Louisville and Tucson mines, all lying along the Tucson-Maid fault in Iron Hill. Here again no very distinctive stage of mineralization can be recognized, nor could the paragenesis be studied in detail, but the bismuth minerals with their associates are distinctly later than the galena. In the Greenback mine, in Graham Park, and along the Tucson-Maid fault, bismuth minerals represent a distinct stage. Evidence to this effect consists of pyrite masses broken and veined by a mixture of chalcopyrite and bismuth minerals. Even individual crystals of pyrite have been broken and the cracks filled with chalcopyrite. To a lesser degree the same phenomenon shows with zinc blende. On the other hand, galena has not been broken so generally, although crystals have been noted in which the cleavage lines are bent, probably by the same deformation that produced fracturing elsewhere (Fig. 8). This Greenback ore body occurs along a small branch of the Tucson-Maid fault, and it is probable that a certain amount of movement along this fault caused some crushing after the deposition of pyrite, blende and galena and before deposition of the "bismuth stage."

It is noteworthy that all occurrences of ore of this "bismuth stage" are found close to the centers of mineralization or along the recognized main trunk channels, and that they appear to be superimposed upon the minerals of the earlier periods.

Detailed Mineralogy of Bismuth Stage

General Associations.—The "bismuth stage" is later than the other three stages, which are represented by pyrite, sphalerite, and galena. In general, its most common mineral is chalcopyrite. Other minerals include galenobismutite ($PbS \cdot Bi_2S_3$), aikinite ($Cu_2S \cdot 2PbS \cdot Bi_2S_3$), hessite ($Ag_2Te$), altaite ($PbTe$), galena, tennantite ($5Cu_2S \cdot 2(Cu, Fe, Zn)S \cdot 2As_2S_3$), alaskaite ($Ag_2S \cdot PbS \cdot Bi_2S_3$), argentite ($Ag_2S$), native gold, and perhaps sphalerite and arsenopyrite. In addition to these minerals bismuthinite is reported in *Professional Paper* 148 (p. 170) and also kobellite, lillianite, and schapbachite, of which the identity is doubtful. Also, small amounts of chalcocite, argentite and native silver, all apparently supergene, are present.

With the exception of native gold, which is usually later than the other minerals of the "bismuth stage," the relative age of the hypogene minerals is difficult to determine. Seldom more than two of them appear in any one specimen and their common boundaries are well rounded and best described as "mutual." The minerals all appear contemporaneous.

Chalcopyrite.—Chalcopyrite, the most common mineral of the "bismuth stage," has been found in all occurrences noted and is prominent in many of the surfaces studied. It is associated with other minerals of this stage and is contemporaneous with them, but seems to avoid close proximity to hessite and gold. It differs in no way from the same mineral of the earlier stages except in its associations.

Galenobismutite.—Galenobismutite ($PbS \cdot Bi_2S_3$) was found in only one specimen from the Greenback. Here it is closely associated with chalcopyrite and with an unusual variety of galena, which gives microchemical tests for bismuth and tellurium but not for silver. This mineral should perhaps be considered a bismuth-bearing altaite, although the etch reactions correspond more closely to those of galena. All three minerals appear contemporaneous, but contain somewhat rounded inclusions of earlier pyrite and blende. The galenobismutite is strongly anisotropic and has a rough fibrous appearance. It nearly matches galena in color, but the two minerals are readily distinguished where etched with hydrochloric acid, the galena turning dark whereas the galenobismutite is unaffected. Galenobismutite was also found in a specimen from the Tucson mine, to be described later under schapbachite (Fig. 3).

Aikinite.—One specimen of ore representing the "bismuth stage" in the Greenback mine contains aikinite ($Cu_2S \cdot 2PbS \cdot Bi_2S_3$), closely associated with the chalcopyrite of the same stage. In places the aikinite contains blebs of native silver which are thought to be secondary, especially as some of the chalcopyrite in this vicinity is altering to chalcocite. In appearance as well as in etch reactions and microchemical tests the aikinite is normal in every way.

Hessite.—Hessite (Ag_2Te) also has been found in the Greenback ore, as well as in ore from the Tucson and Louisville mines and from Breece Hill and in borrowed specimens merely marked "Leadville." In general chalcopyrite is absent from specimens that contain hessite or is present only in small amounts and at a distance from the telluride. The usual close associates of the hessite are altaite or galena of the "bismuth stage." It is the favorite host mineral for native gold. In different specimens the hessite varies from a darker greenish brown to a lighter pinkish brown cast. The darker variety is somewhat less sectile, scratching partly to powder and partly to shavings. Both varieties give identical etch and microchemical tests, however.

Altaite.—Altaite ($PbTe$) is found in many specimens of ore from the Greenback mine, as well as in ore from the Tucson and Louisville mines on Iron Hill, from the Garbutt mine on Breece Hill, and in another specimen known only to have come from somewhere in Breece Hill. In all specimens this mineral fails to effervesce when etched with nitric acid. In places the microchemical test for tellurium is weak, suggesting as a better designation bismuth-and-tellurium-bearing galena. In one specimen the altaite contains several inclusions of normal galena, perhaps of the galena stage, showing strong evidence of cubic cleavage. Here at least the altaite is distinctly lighter in color on the polished surface (Figs. 3, 5 and 7).

Galena.—Galena occurs in two or three varieties, which differ from each other and from the early galena in appearance, intensity of etch reactions, and elements shown to be present by microchemical tests. One variety, which was found in appreciable amounts, is so pure and constant in composition that it has been analyzed and fully described as a distinct variety. Its formula[3] approximates $Ag_2S \cdot Bi_2S_3 \cdot 11PbS$. Another variety shows the presence of a small amount of bismuth, and its silver, if present, is too low to give a microchemical test. Yet another variety has both bismuth and silver in sufficient quantities to show in microchemical tests. Finally, still another variety contains, in addition to silver, recognizable quantities of tellurium. No two of these varieties of galena occur together in the same polished surface, though all were found in the same ore body. As yet it is not known whether they represent definite chemical compounds or solid solutions of the various elements in galena. Choice between these alternatives would require a large amount of analytical work, but the homogeneity of the one variety of which the formula has been quoted suggests a definite compound.

Tennantite.—The scarcity of the gray coppers is commented on by Loughlin,[4] who records the occurrence of tetrahedrite in the Ibex mine in relations that suggest that it belongs to the "bismuth stage." Loughlin and Behre[5] mention tennantite ($5Cu_2S \cdot 2(Cu,Fe,Zn)S \cdot 2As_2S_3$) in the Lillian ores, and state that from analogy elsewhere it may be correlated with the occurrence of gold and lillianite. The writer has found it in the Greenback ore body in these relations, as well as in ore from the Printer Boy vein on the north slope of Printer Boy Hill. Here it is associated with chalcopyrite, and the same ore apparently contains a lead-bismuth mineral, unfortunately in such small amounts that it could not be identified positively. The tennantite was perhaps contemporaneous with chalcopyrite, veinlets of which cut normal galena. In the Elva Elma tunnel on Breece Hill brecciated ore also contained a small amount of tennantite, but there the original association was obscured by oxidation.

Every specimen of tennantite gave microchemical tests for both arsenic and antimony, with arsenic dominant. It seems likely that the tennantite was deposited in all these places in the same relative position chronologically as the minerals of the "bismuth stage."

Alaskaite.—Alaskaite ($Ag_2S \cdot PbS \cdot Bi_2S_3$) is found in only one specimen, which came from the Lillian mine on Printer Boy Hill. The mineral occurs as residual nodules in a mass of cerussite, hematite, and other carbonates and oxides. A few tiny, well-rounded inclusions of early pyrite and galena and a small amount of gold are also present. The gold occurs partly surrounding small cavities in the alaskaite, where it appears supergene, and also as narrow films between the pyrite inclusions and the alaskaite. It is also found as irregular, somewhat rounded inclusions in the alaskaite itself, apparently contemporaneous with its host and quite different from the occurrence described above where veinlets of gold cut hessite (Figs. 3, 4 and 6).

Argentite.—Hypogene argentite (Ag_2S) seems scarce in the Leadville district. One specimen from the deeper levels of the Louisville mine on Iron Hill shows a few irregular rounded inclusions of this mineral in silver-and-bismuth-bearing galena of the "bismuth stage." The argentite so closely resembles the more common hessite in appearance that its identification is possible only by etch and microchemical tests. The

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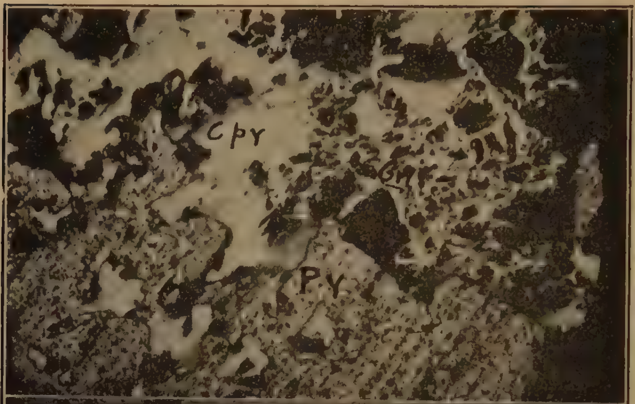

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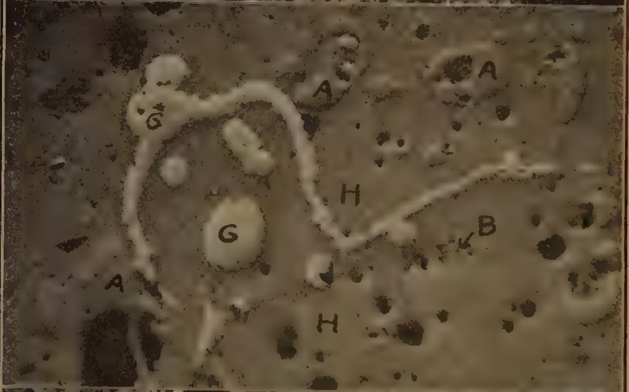

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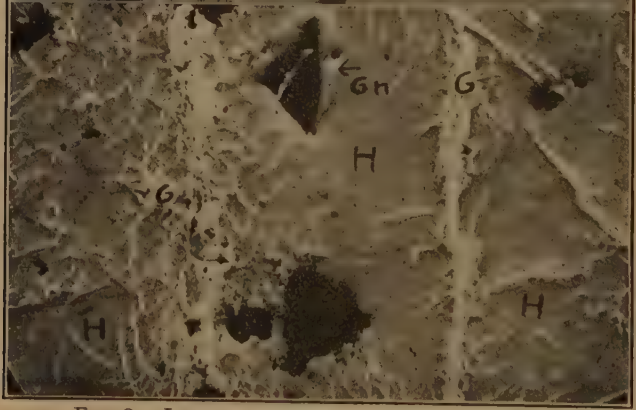


Fig. 2.—Louisville mine. × 50.

Chalcopyrite (*Cpy*) and silver-and-bismuth-bearing galena (*Gn*) of the "bismuth stage," showing relations to pyrite (*Py*) of an earlier stage.

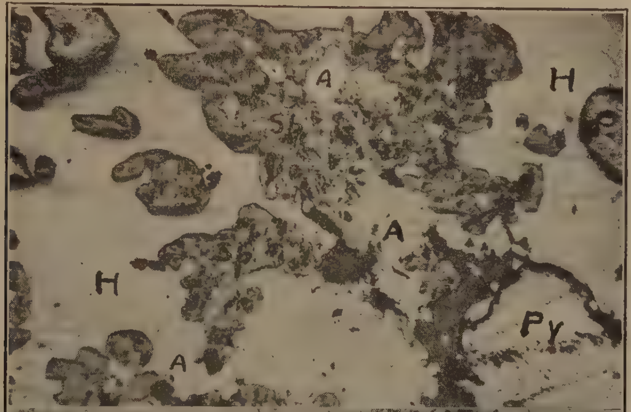
Fig. 3.—Minerals from Tucson mine. × 70.

Gold (*G*) in hessite (*H*). Gold is in round inclusions and in veinlets that cut hessite, the dominant mineral in the surface. The mineral *A*, showing strong relief, is bismuth-bearing altaite. Small inclusions of a rough fibrous mineral (*B*) are galenobismutite. Black areas are pits in surface.

Fig. 4.—Minerals from Iron Hill. × 85.

Gold (*G*) cutting hessite (*H*) in many ramifying veinlets. One inclusion of galena (*Gn*) of the earlier mineralization, showing triangular pits. Black areas are pits in surface.

mineral appears contemporaneous with its host mineral and is definitely hypogene. It is the only hypogene argentite that the writer has found in the study of many polished surfaces from this district. By contrast supergene argentite, associated with cerussite or with secondary chalcocite and covellite, is common at Leadville, though small in total amount.



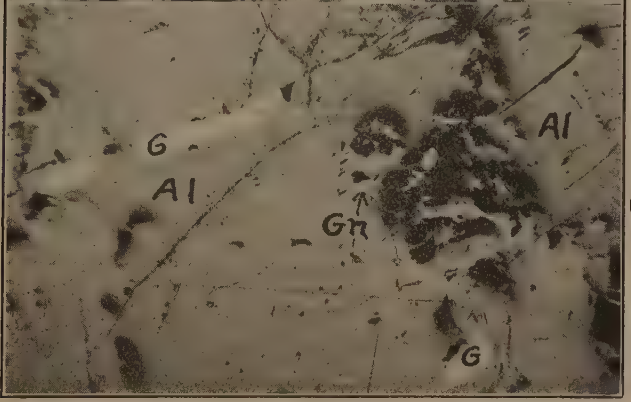


Fig. 5.—Minerals from Breece Hill. × 70.

Hessite (*H*); silver-and-bismuth-bearing altaite (*A*) of "bismuth stage," showing relations to pyrite (*Py*) and sphalerite (*Sp*) of earlier stages. Dark gray mineral is a later carbonate.

Fig. 6.—Minerals from Lillian mine. × 85.

Gold (*G*) in alaskaite (*Al*). Several small inclusions of galena (*Gn*) of an earlier generation are present. Gray minerals in veinlets in alaskaite are secondary carbonates. Black areas are pits in surface.

Many specimens of galena from various parts of the district show, on etching with HNO_3, numerous lath-shaped inclusions arranged along cleavage planes of the mineral. At first these were thought to be argentite, but shipments from the same stopes as those from which some of the specimens were collected were too low in silver to agree with such an identification; furthermore, some specimens of the included mineral were found to be strongly anisotropic, although generally the specimens were not tested for this feature. Similar inclusions are found in some of the galena of the main period of mineralization, and also in some of the silver-and-bismuth-bearing galena, and in the so-called altaite of the "bismuth stage." The writer has been unable to identify this mineral, but the inclusions tested seemed definitely not to be argentite.

Native Gold.—Native gold occurs in various specimens from Breece and Iron Hills, where it cuts hessite in veinlets and is distinctly later than the latter, but is thought to belong to the same "bismuth stage" of mineralization and to be hypogene (Figs. 3 and 4). Some of the veinlets are large enough to be seen with the naked eye and are connected with many smaller ramifying veinlets of the same metal visible only under the microscope. This association of free gold with hessite is surprising, as it would seem much more natural to find it with the gold-silver telluride, petzite. However, careful tests have failed to show gold present as a constituent in the composition of the host mineral. Indeed, none of the gold-bearing tellurides has been found so far in the Leadville district.

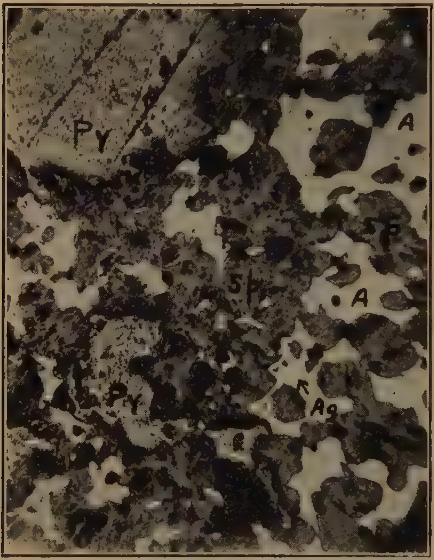


FIG. 7.—MINERALS FROM BREECE HILL. × 70.

Pyrite (*Py*) and sphalerite (*Sp*) of earlier stages of sulphide deposition. Silver-and-bismuth-bearing altaite (*A*) fills interstices between earlier minerals, and in places veins them. Hessite with gold veinlets is also present in specimen but does not show in photograph. One small area of native silver (*Ag*) is present. It appears hypogene, and in this relation is uncommon in the bismuth stage as known to the writer, and it is not mentioned in the text. However, small amounts of supergene silver are common.

Gold also occurs in one specimen from the Lillian mine on Printer Boy Hill. Here it is associated with alaskaite and structurally its occurrence differs considerably from that described above. (See Figs. 3, 4 and 6.)

The association of native gold with bismuth minerals is apparently not uncommon in other districts throughout the world. The writer has noted it at the Tiger mine, Breckenridge, Colo.; it is reported by Bugge[2] from Bleka, Norway; by Shannon[6] from Boise County, Idaho, and by Warren[7] from British Columbia.

Sphalerite.—Sphalerite occurs in small amounts in some of the specimens from the Greenback mine, where it shows mutual boundaries to silver-bismuth-bearing galena and to chalcopyrite. It is the iron-bearing marmatite variety and does not differ from the earlier blende of stage 2, but is thought to belong to the "bismuth stage" because of its relations.

Arsenopyrite.—Professional Paper 148 (p. 151) mentions arsenopyrite from the Moyer mine and also from the Tucson mine, both on Iron Hill. No mention of its probable age is made. In a later article (ref. 5, pp. 223 and 229), arsenopyrite is placed with a question mark as contemporaneous with the first pyrite deposition and earlier than the sphalerite and galena, a relation that would be consistent with common ideas of paragenesis. The writer has found this mineral in a suite of specimens from the dump of the First National mine in Iowa Gulch. These specimens consist of manganosiderite veined and impregnated with pyrite, sphalerite, galena and arsenopyrite. Vugs contain drusy masses of galena and arsenopyrite crystals resting on a mixture of fine-grained manganosiderite, pyrite and sphalerite. In one specimen a crystal of arsenopyrite seems to be resting on galena. In places the crystals of galena and arsenopyrite are coated with rhombs of later manganosiderite. The arsenopyrite is certainly later than the pyrite and sphalerite and probably also later than the galena. Microscopic study of polished surfaces confirms these relations. Arsenopyrite has also been found on a shaft dump in Empire Gulch about one mile south and a little east of the First National mine. Here age relations of arsenopyrite to other sulphides are not shown, as it occurs alone in the manganosiderite. Arsenopyrite is not a common Leadville mineral; its origin is obscure, and the relations described above even suggest that it may belong to the "bismuth stage" of deposition.

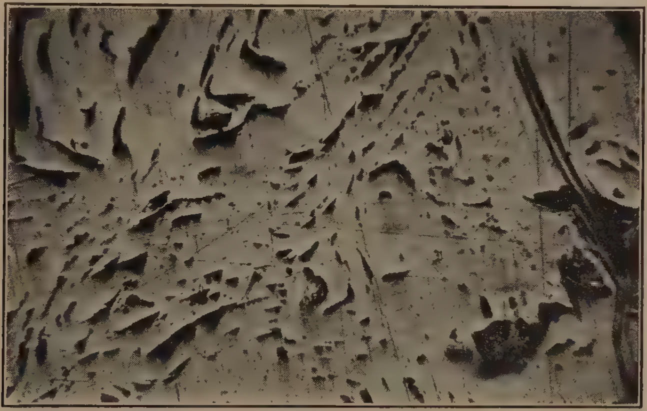


FIG. 8.—GALENA OF EARLIER STAGE OF MINERALIZATION. × 50.
Shows distorted cleavage lines caused by deformation after its deposition and before deposition of chalcopyrite and galena of the "bismuth stage," which do not show in photomicrograph but are present in specimen.

Intergrowths of Bismuthinite and Argentite.—Examples of an intergrowth of bismuthinite and argentite have been reported (ref. 4, p. 169) from the Lillian mine and apparently belong to the "bismuth stage" of mineralization. The material was said to have been accompanied by free gold, though no gold was found in the polished sections. The writer has attempted to obtain specimens of such ore but without success. Several specimens of related ore show steel galena, a variety unusual to Leadville. Polished surfaces of this material exhibit a microscopically intimate, irregular mixture of galena and sphalerite. The galena is normal in every way, but lacks the usual triangular cleavage pits. There is not enough silver or bismuth present to give microchemical tests, and there is not even evidence that this material belongs to the "bismuth stage."

Schapbachite.—Specimens from the Cambrian quartzite on the tenth level of the Tucson mine were furnished by Mr. George O. Argall. From these he reported a lead-bismuth-silver mineral, which he identified as schapbachite, because of blowpipe tests and physical appearance. He described the occurrence[1] as consisting of four bands or layers: (1) an inner zone 1/16 in. thick of fine galena with a little blende and pyrite on quartzite (this surface was found by the present writer to be quite irregular); (2) a band 1/4 in. thick of blende and pyrite, with a few spangles of galena, forming a distinct crust; (3) irregular grains of chalcopyrite lying mostly in cavities between the outermost crystals of the 1/4-in. band of blende and pyrite (layer 2); (4) massive crystals of galena 1 in. thick, some coated with a film of the argentite-bismuthinite intergrowth.

The two specimens studied were supposed to represent the coating here designated as layer 4 on the inside of the galena crystals in places where it had thickened to a good-sized band. A careful restudy of both specimens was undertaken by the present writer. One contains chalcopyrite, altaite and galenobismutite, apparently of the same age, with minor inclusions of pyrite and sphalerite of earlier age. These determinations were aided by etch tests and microchemical reactions. The altaite gave a strong microchemical test for bismuth, and none of the minerals contained enough silver to give a microchemical test for that element. The second specimen, marked "schapbachite," yielded assays of 14 oz. gold and 10,000 oz. silver to the ton, and 44 per cent lead. The polished surface showed the same bismuth-bearing altaite and hessite, apparently contemporaneous, in ratios of about 3 to 1. Locally the hessite contained narrow veinlets of free gold. The other minerals present were pyrite and galena in a few small grains (Fig. 3). It appears, therefore, that the presumptive schapbachite is a mixture of hessite and bismuth-bearing altaite with associated gold.

ACKNOWLEDGMENTS

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Structure and Ore Deposition at Cartersville, Georgia

By Thomas L. Kesler*

(New York Meeting, February 1941)

The Cartersville mining district, 35 miles northwest of Atlanta, Ga., has been of varying but continuous importance in the southern mineral industry during the past century. Noted chiefly for its production of brown iron ore, manganese oxide ores, barite, sienna, and magnesian limestone, the district and its environs have produced brick and tile clays, slate, gold, bauxite, and graphitic schist. Minor deposits of serpentine, sericite schist, copper ore, and red iron oxide have been prospected.

The obvious deposits of brown iron ore, together with some associated specular hematite, were mined out years ago, although a little ore was left in the workings. Moderately steady production of sienna reached a peak about 1930, then declined rapidly. Manganese mining passed through a relatively active period from the World War to 1931, but has subsided to a small but rather constant output for the Birmingham market. However, the White Manganese Corporation has prepared for possible increased production by constructing a new washer capable of handling about 300 tons of ore per day. Principal activity in the district proper has centered for some years in the production of barite and magnesian limestone.

GENERAL GEOLOGY

Geologic relations of the ore deposits of this district are more or less similar to those of many Appalachian districts. The lowermost Cambrian formation, heretofore called Weisner[1] in this region, supposedly partly or wholly equivalent to the Erwin and Hesse quartzites as recognized to the northeast, is overlain conformably by the Shady† formation, also of Lower Cambrian age. In the Cartersville district, the sedimentary rocks of these formations were folded with increasing intensity eastward, and were recrystallized.

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[1] References are at the end of the paper.

† First called "Beaver" by Hayes.[1] Later correlated paleontologically with the Shady of Tennessee.

The Weisner formation, of unknown thickness, is made up of sericite and muscovite schists interbedded with quartzites. The Shady is an areally extensive series of crystalline limestones, for the most part dolomitic, interbedded with and grading into sericite and muscovite schists whose carbonate content has a wide and erratic range; its thickness also is unknown here. Both formations have been feldspathized considerably in places.

The intimately related deposits of iron, sienna, barite, and manganese occur in the zone in which open folds merge eastward into overturned isoclinal folds. In general, the anticlines have been stripped of the dolomite and schist of the Shady formation by erosion, leaving the underlying resistant quartzite beds in the Weisner to form the peaks and ridges. The dolomite and schist of the Shady formation, with their weathered residual blanket in which the commercial ores occur, remain on the flanks of the anticlines and in the lowlands, most of which are underlain by synclines. Where the uppermost quartzite bed of the Weisner formation dips beneath the ore-bearing residual blanket on the limbs of folds, it is called locally the "footwall" or "sand wall." Quartz, believed to be of hydrothermal origin, has replaced the dolomite extensively in places, and crops out as residual jasperoid knobs; for instance, those prominent south and west of the Paga mines (area 1). It is also found as detached masses in the mine workings, and is confused commonly with quartzite.

Three factors of importance must be considered in determining the origin of the ores: (1) their present (postweathering) mineral composition as contrasted with original (preweathering) mineral composition; (2) their lithologic associations; and (3) any geologic structures that characterize their occurrence.

Limonite and goethite comprise the brown ores, and specularite has been the principal ore mined at a few localities. Sienna is simply finely divided brown ore thoroughly disseminated through residual clay, fine muscovite, and quartz. Exclusive of a sparsely developed supergene variety, barite occurs as rounded and angular white crystalline masses in residual clays. Manganese occurs as hard and soft oxide ores in residual clays.

The brown ores have been derived from the oxidation and hydration of concentrated bodies of pyrite, specularite, and possibly iron carbonate. Where pyrite and specularite were not sufficiently concentrated to form brown ore through weathering, bodies of sienna have been formed. These are of two varieties: (1) finely divided brown ore mixed with structureless clay, fine muscovite, and quartz representing slumped residuum of weathered dolomite that contained disseminated pyrite or specular hematite; (2) a banded or layered variety, which is the weathered but essentially undisturbed counterpart of laminated specular hematite. Barite identical to that mined from dolomite residuum occurs in veins and replacement masses in fresh dolomite, and weathering of the rock frees the mineral to form residual deposits. Up to the present, no preweathering (source) mineral for the manganese oxide ores has been discovered, but the intimate relationship between manganese and the other ores, whose origins have been solved, reflects a very close genetic kinship. Therefore, the origin of the manganese must, at present, be traced through its geologic associations, as the evidence presented below will indicate.

It is seen from the foregoing discussion that only two of the postweathering ores are not typical products of supergene alteration—specularite and barite. The exposures of massive barite in the dolomite of the Shady formation have led to an earlier interpretation of hypogene[2] origin. The occurrence of barite deposits in zones of shattering also has been reported.[3] However, discussions of the origins of brown iron ore, specularite, manganese, and sienna have been variously vague, speculative, and noncommittal, largely as a result of partial familiarity with the scanty evidence available. Original sedimentation, secondary concentration by surface and subsurface drainage, and the action of thermal waters of meteoric or uncertain origin, all have been inferred.

There is a common belief that the lower portion of the Shady formation contains source minerals of the present ores (particularly of manganese) which were deposited chemically or mechanically during original sedimentation, and that weathering has permitted concentration of the present deposits. This view argues in favor of more or less uniform distribution of supergene deposits coextensive with the residuum of the parent formation, particularly in the Cartersville district, where, during reduction of the land surface, favorable geologic structure and deep weathering would have promoted the formation of oxide ores with a minimum of migration.

To the contrary, the Cartersville ores are strictly localized, and occur under widely divergent conditions of drainage and with no relation to altitude. The sole controlling factors in the deposition of source minerals were the second and third genetic factors listed above; namely, lithologic associations and structure. Most of the ores were deposited in dolomite and calcareous schists of the Shady formation, and faults and fractures are in evidence at all deposits where bedrock is exposed sufficiently to permit structural analysis.

In an earlier paper,[4] the writer has called attention to the relationship between oblique and transverse faults and the positions of ore deposits, holding that the entire group of ores represents a close association of minerals that were introduced along faults and fractures by hydrothermal solutions from a magmatic source, and modified in part by oxidation. The factor of faulting in the localization of the ores is, in itself, important evidence of preweathering hydrothermal deposition, for it is obvious that ascending solutions seek out channels where the continuity of overlying rocks is broken, whereas the circulation of descending solutions is practically unconfined within the zone of leaching of the dolomite. The characteristic but not invariable occurrence of the deposits at or near the contact between the Shady and the Weisner formations is the normal result of emergence of mineral-bearing hydrothermal solutions from the relatively inert quartzites and schists of the older formation, and their immediate attack on the highly susceptible overlying dolomite and calcareous schists. Here, the solutions deposited ore minerals that included barite, carbonates, chalcopyrite, galena, luzonite, pyrite, quartz, specularite, sphalerite, tennantite, and, apparently, a source mineral of the manganese oxides.

Subsequent erosion of the land surface lowered the zone of weathering within the range of these hydrothermal deposits, forming iron and manganese oxides, chalcocite, covellite, malachite, chalcanthite, and cerussite. Some migration of mineral matter would be expected in this superficial modification, resulting in local deposition of oxides and carbonates near their source minerals; however, considerable dispersal would occur during transfer by ground and surface waters, and its aggregate result on the ore deposits would be loss rather than gain. Thus, the present ores are surface residues that have not moved appreciably from the positions in which their source minerals were deposited, and field evidence shows that they grade downward into unweathered ores.

The surficial oxidation of concentrated bodies of pyrite, forming at least some of the relatively shallow brown ore deposits, involves an economic possibility hitherto overlooked. Some of these pyrite lodes may be sufficiently extensive for exploitation. Another feature of interest relating to both iron and manganese oxide ores is their characteristic but variable phosphorus content. McCallie[5] believed that apatite is the chief source of phosphorus in the brown ores. However, the writer has found a complex association of strengite and other iron phosphates at the Iron Hill mine, 6 miles southeast of Cartersville, and these probably constitute the more important sources of phosphorus in the Cartersville ores.

EXAMPLES OF STRUCTURAL CONTROL

The mining belt coincides approximately with a belt of ridges and peaks shown in Fig. 1, the current topographic base for the district. Four areas to be discussed are outlined and designated by numbers. In Figs. 2, 3, 4 and 5 these areas are enlarged to four times the scale of the base map, in order to show the mines and geology. Names of well-known workings are shown, although some of the properties have changed hands since these names were applicable.

The generalized nature and not infrequent errors of the base map, published in 1906, have had a profound bearing on the writer's geologic work in the Cartersville district, and a brief explanation is appropriate

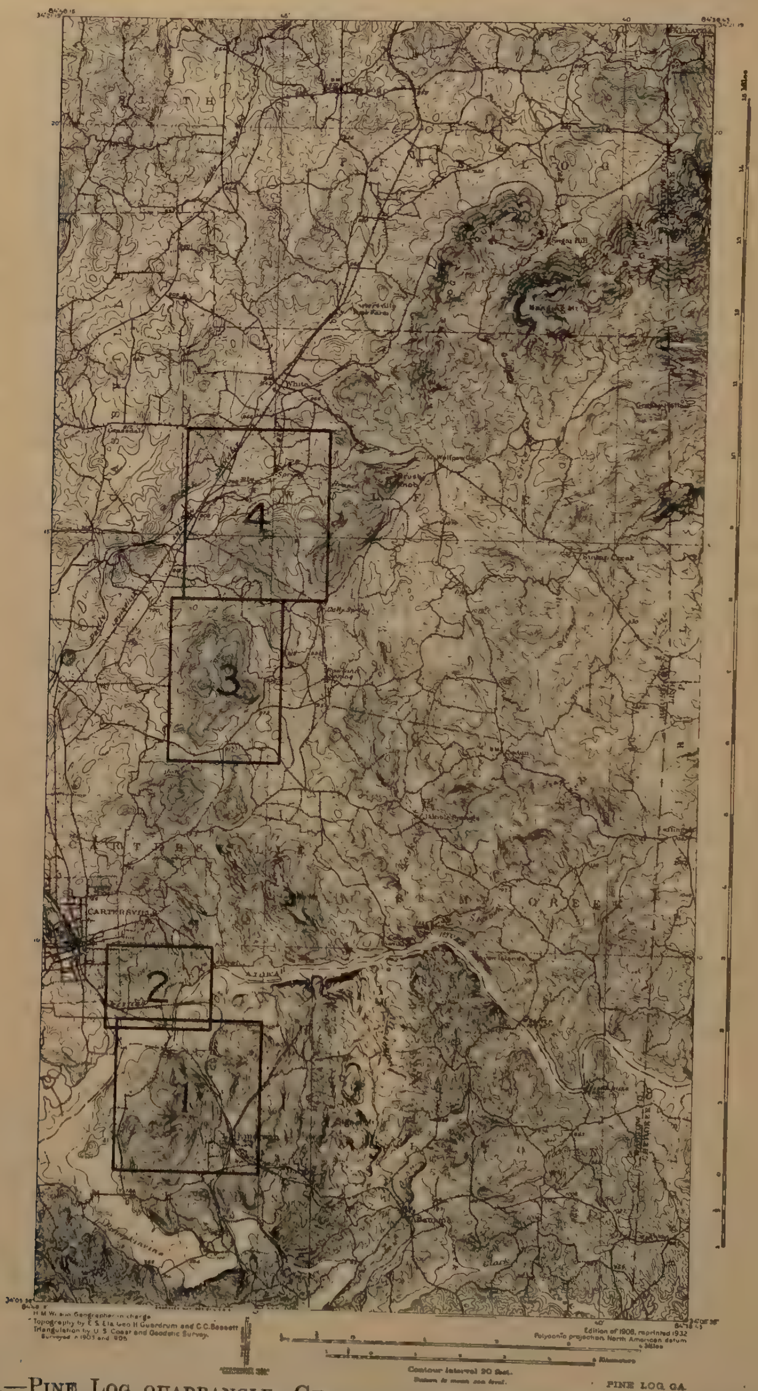
4
3
CARTERSVILLE
2
1
H M Wilson Geographer in charge
Topography by E S Ela Geo H Guerdrum and C C Bassett
Triangulation by U S Coast and Geodetic Survey
Surveyed in 1903 and 1905
Edition of 1906, reprinted 1932
Polyconic projection North American datum
Miles
Kilometers
Contour interval 20 feet.
Datum is mean sea level.
PINE LOG GA

FIG. 1.—PINE LOG QUADRANGLE, GEORGIA, WHICH INCLUDES THE CARTERSVILLE MINING DISTRICT. THE FOUR AREAS OUTLINED ARE ILLUSTRATED IN FIGS. 2, 3, 4 AND 5.

here. Inaccuracies in topography, together with the rugged and wooded character of the mining belt, have made it impossible to plot many observed features in their proper relative positions. The Geological Survey is preparing a new base map of the district, but for immediate needs it has been necessary to correct the topography of the figured areas largely by re-sketching, aided to some extent by a set of distorted aerial photographs. Therefore, when the new base map is available and space relationships of geologic details are better known, it will be possible to show with greater accuracy structural conditions described in this paper.

The known faults, shown by solid lines in Figs. 2, 3, 4 and 5, are visible dislocations, and do not involve the usual amount of supposition that renders many Appalachian faults arbitrary and intangible. The dashed lines, indicating fault zones and inferred faults, connect closely spaced evidences of rupture that may or may not reflect continuous lines of faulting. The faults shown in Figs. 2 to 5, therefore, should not be regarded as the total number present in these selected areas, but only as those for which evidence has been found to date.

Area 1

Area 1 (Fig. 2) lies between the village of Emerson and Etowah River. The area contains numerous mineral deposits among which three show unusually clear relationships to faults. One of these faults is reflected by the uppermost quartzite in the Weisner formation, which dips 60° NW. beneath residuum of the Shady formation on a low, conical hill 1.2 miles northwest of Emerson and 0.5 mile northeast of the Paga Mining Company's No. 1 open cuts. The quartzite passes northeast from this hill into another 0.3 mile south of the Georgia Peruvian Ochre Company's mine, where it turns eastward and southward to form the nose of an anticline. On top of the conical hill, the quartzite has been offset in a direction about N. 80° W., the south side having moved about 250 ft. west with respect to the north. On the northwest slope of the hill, and just below the offset, a deposit of barite has been mined from the weathered debris of the dolomite. Identical barite occurs in veins and replacement bodies in the fresh, fissured dolomite 0.8 mile northwest at the grinding plant of the Thompson-Weinmann Co. on Etowah River. Post-barite silicification along the fault formed much jasperoid at the contact. The jasperoid contains fossils typical of the Shady formation.

As shown in Fig. 2, the eastern portion of the combined Paga No. 1 opencuts comprises three distinct workings that extend southeast into a hillside. The extreme northeast cut shows clear evidence of faulting. Its southwest wall, a narrow partition separating it from the adjacent cut, exposes dolomite of the Shady formation, and its residuum, overlying quartzite and schist of the Weisner formation. The series dips northwest. The northeast wall, however, exposes only weathered and unweathered dolomite like that at the top of the series in the southwest wall. This indicates a vertical or very steep offset of more than 40 ft., the southwest side having moved upward. From surrounding structural indications, the vertical displacement may exceed 150 ft. The fault strikes N. 40° W.,

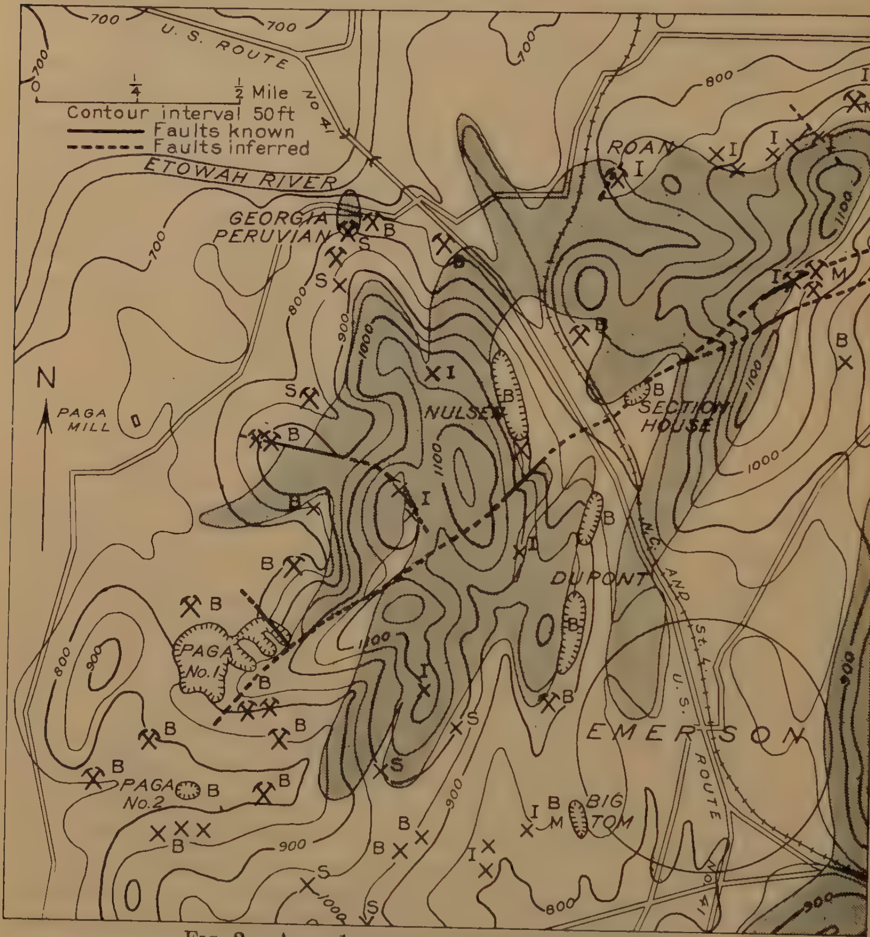

FIG. 2.—AREA 1, NORTH AND WEST OF EMERSON.

Shaded portion represents the Weisner formation; unshaded portion, the overlying Shady formation. Both are of Lower Cambrian age. Abbreviations: *B*, barite; *M*, manganese ores; *S*, sienna ("ocher"); *I*, brown iron ore and specular hematite.

and mining operations have followed it because of the abundance of barite freed from the dolomite by weathering.

A long series of fault indications, which may reflect a continuous zone of dislocation, extends northeast from the Paga cuts, passing immediately south of the Nulsen mine to the crest of a ridge 1.1 miles north northeast of Emerson, where it shows plainly as two oblique faults that intersect the uppermost quartzite beds of the Weisner formation. The quartzite strikes northeast and has an average dip of 40° southeast beneath the weathered Shady, so that the crest of the ridge reflects the contact between the two formations. The two offsets of the contact are about 200 ft. apart, the northern one having a horizontal displacement of 100 ft., the southern about 75 ft. Along each fault the south side has moved eastward with respect to the north. Early mining for manganiferous iron ore was carried on directly in the north offset, and later operations for manganese have been extended about 300 ft. northeastward, along and adjacent to the line of the fault. The south fault appears less favorable for ore minerals, and has not been prospected, but the local abundance of meagerly fossiliferous jasperoid within the offset shows the effect of silicification along the fault zone. It is interesting and no doubt pertinent to note that no ore body of consequence has been found along the ridge except in this clearly faulted locality.

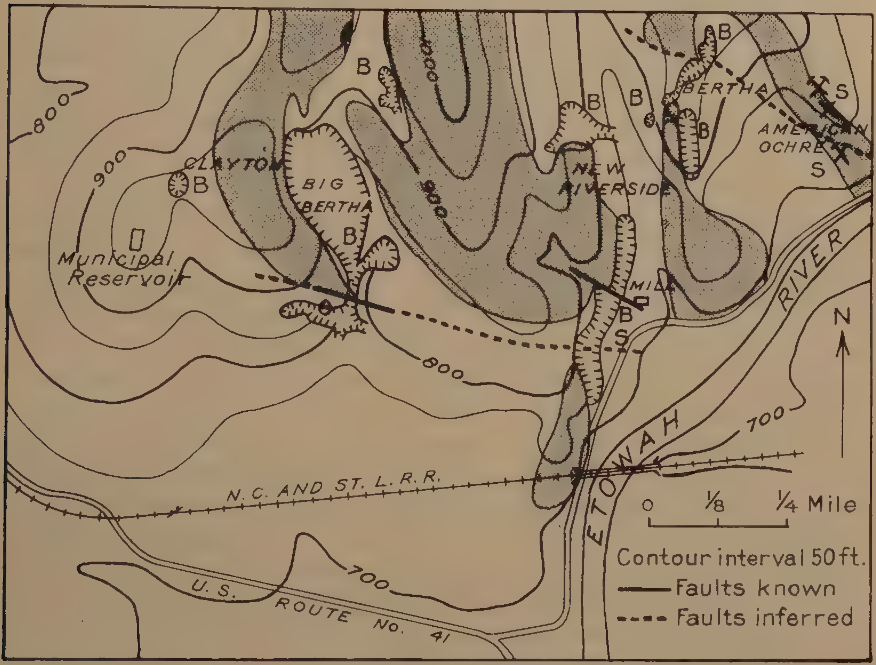

FIG. 3.—AREA 2, INCLUDING NEW RIVERSIDE AND BERTHA MINES. Shaded portion, Weisner formation; unshaded portion, Shady formation. Abbreviations as in Fig. 2.

Area 2

In the vicinity of the New Riverside Ochre Co. (Fig. 3), an evident structural break has been exposed by erosion and mining directly west of the sienna mill. The uppermost quartzite bed in the Weisner, striking north 5° E. and dipping 60° SE., has been stripped of sienna and barite-bearing dolomite residuum. It ends abruptly on the north side of an east-draining ravine. On the south side of the ravine, mining has been carried on in the residuum for about 200 ft. farther west, ending against similar quartzite. This indicates a steep oblique fault trending northwest toward the great cut made by the Bertha Mineral Co. on the west side of the ridge. On the south side of the ravine Shady fossils are preserved in both barite and jasperoid.

About 0.3 mile north of this fault, openings on both sides of the principal creek have exposed large masses of light dove-colored dolomite, the parent rock of the residuum. Irregular veins and masses of barite up to a foot in thickness reflect intimate prebarite fissuring of the rock. In the barite, and particularly along its contacts with the dolomite, sulphide minerals occur in fine grains. A polished section of one of the sulphide areas in barite shows sphalerite enclosing small areas of galena. Marginal to the sphalerite are small areas of covellite, a product of the weathering of a copper mineral.

A fault is exposed at the south end of the big cut of the Bertha Mineral Co. west of the New Riverside property. In the west wall of the entrance to the lowest level, completely leached dolomite of the Shady formation, now a chocolate-colored clay with thin schist partings, strikes N. 75° W. and dips 50° SW. An inverted V-shaped zone of leached breccia and gouge 4½ ft. thick at the base of the exposure separates the weathered dolomite on the south from interbedded quartzite and pale greenish yellow sericite schist of the Weisner formation, also much weathered, on the north. The Weisner strata are nearly horizontal at the fault contact, but assume a gentle dip to the northeast less than 50 ft. from the fault. The fault is normal and very steep, and trends toward the workings of the New Riverside Ochre Co. south of the fault described previously, but neither the horizontal nor vertical components can be estimated. No barite was observed in or immediately adjacent to the fault zone, and neither fissuring nor brecciation was apparent in either wall, but a deep gully about 60 ft. south of the fault exposes abundant barite in the thoroughly leached dolomite. Occurrence of the mineral here is identical to that in fresh dolomite, as described above, and here too reflects a high degree of prebarite fissuring contemporaneous with the faulting. It is probable that the gouge from the soft schists of the Weisner formation plugged the fault zone, preventing circulation along it; instead, the solutions circulated through the adjacent fissured dolomite, depositing barite and incidental ore minerals.

A roughly stratified blanket of silt, sand and gravel 6 ft. thick covers the faulted bedrock described in the preceding paragraph. It is interesting to note that although such alluvium in the district commonly contains quartz pebbles and boulders, and although some of the pebbles here are quartz, most are barite. Both types of pebbles are water-worn, ranging in size from fine gravel to a maximum dimension of about 1½ in. Such evidence of mechanically transported barite of such coarseness is extremely rare in the district, and is found always where gradients are very steep.

Area 3

In spite of the fact that geologic work has not been completed in this area, as indicated in Fig. 4, attention is directed to two localities in which there is a clear relationship between faulting and localization of ore minerals.

One mile northwest of the Dobbins manganese mine, and 0.2 mile southeast of the Vaughn mine, the west limb of a prominent anticlinal ridge is reflected in the uppermost quartzite beds of the Weisner formation, which have an average strike of N. 15° E. and a dip of 50° NW. A series of very old specular hematite workings is situated in a faulted offset of the quartzite. The horizontal displacement is approximately 300 ft., and the south side has moved northwest with respect to the north. Specular hematite, clearly formed by the replacement of laminated and possibly calcareous sericite schist of the basal Shady formation, is plentiful about the old workings, but does not occur beyond the vicinity of the fault in either direction. The offset has a trend of about N. 35° W. toward the Vaughn mine, which is situated across the valley of a small southwest-flowing creek. The manganiferous iron ores of the Vaughn mine occur in the usual slumped residuum of dolomite of the Shady formation, with much jasperoid, and the original rock structures here are not preserved; however, space relationships, which are clear at this place, suggest strongly that the original ore minerals of the Vaughn mine were deposited in and adjacent to the same fault that contains the ore of the older iron mine.

One-half mile east of the Dobbins mine, a linear series of shallow excavations for manganiferous brown ore is oriented N. 55° W. (Fig. 4). This narrow ore zone marks a fault contact between the Shady formation on the southwest side and a small area of the Weisner formation on the northeast. Silicified dolomite of the Shady formation, with fractures impregnated by supergene brown iron ore, crops out plentifully along the fault adjacent to quartzite of the Weisner. The fault appears to terminate abruptly at both ends, the movement having been absorbed by soft recrystallized shales. Ores are found only along and adjacent to the fault.

South of this fault, a west-trending line of disturbance begins at a small brown iron-ore mine and passes westward through an adjacent manganese prospect toward the Dobbins mine. Whether it crosses the narrow alluvial valley of a small southwest-draining intermittent stream (Fig. 4) is not known, but evidence of structural discordance is found on the lower southwest slope of the hill immediately east of the Dobbins mine, and again in the saddle between this hill and the main ridge to the

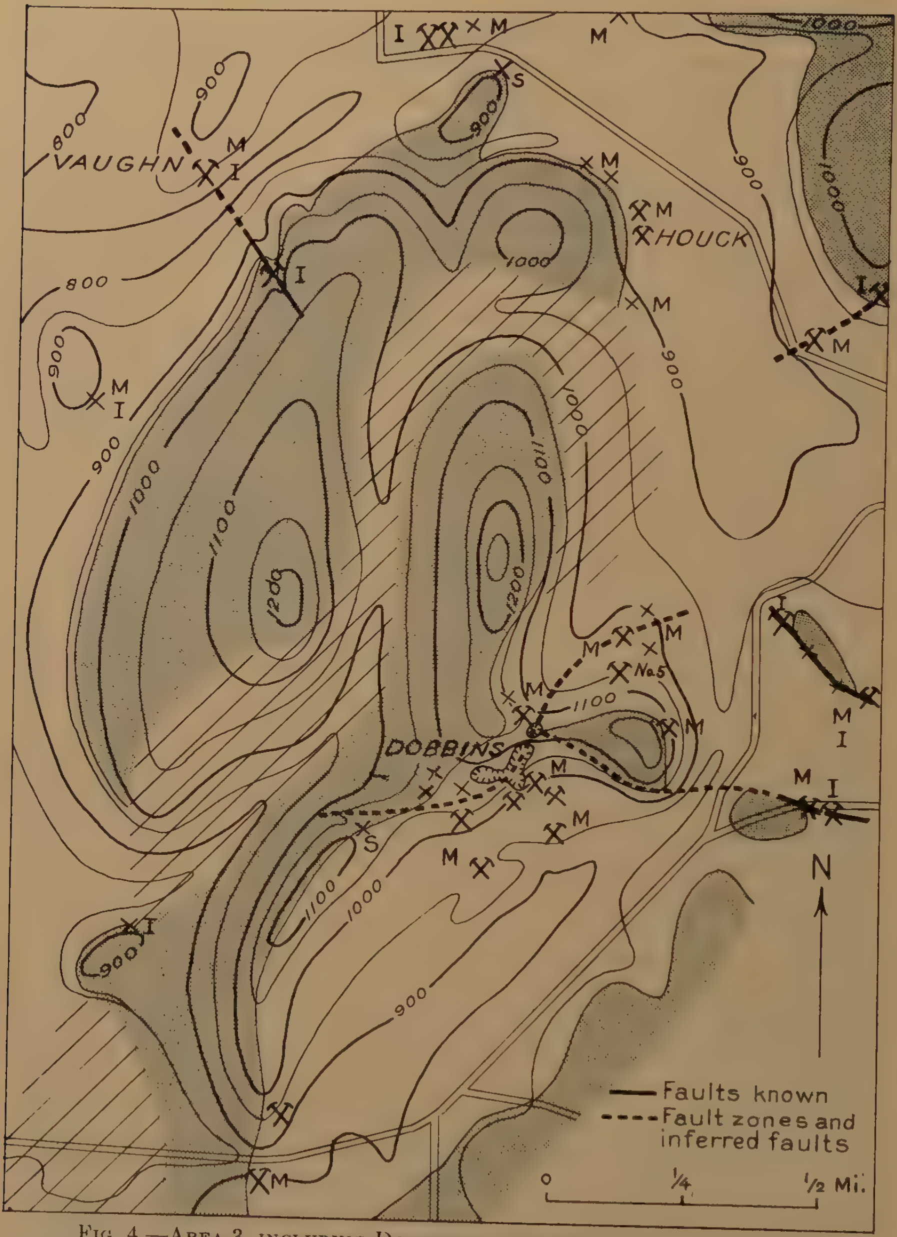

Fig. 4.—Area 3, including Dobbins manganese mine and vicinity. Shaded portion, Weisner formation; unshaded portion, Shady formation. Areas in which geologic work is not yet completed are shown by diagonal lines. Abbreviations as in Fig. 2.

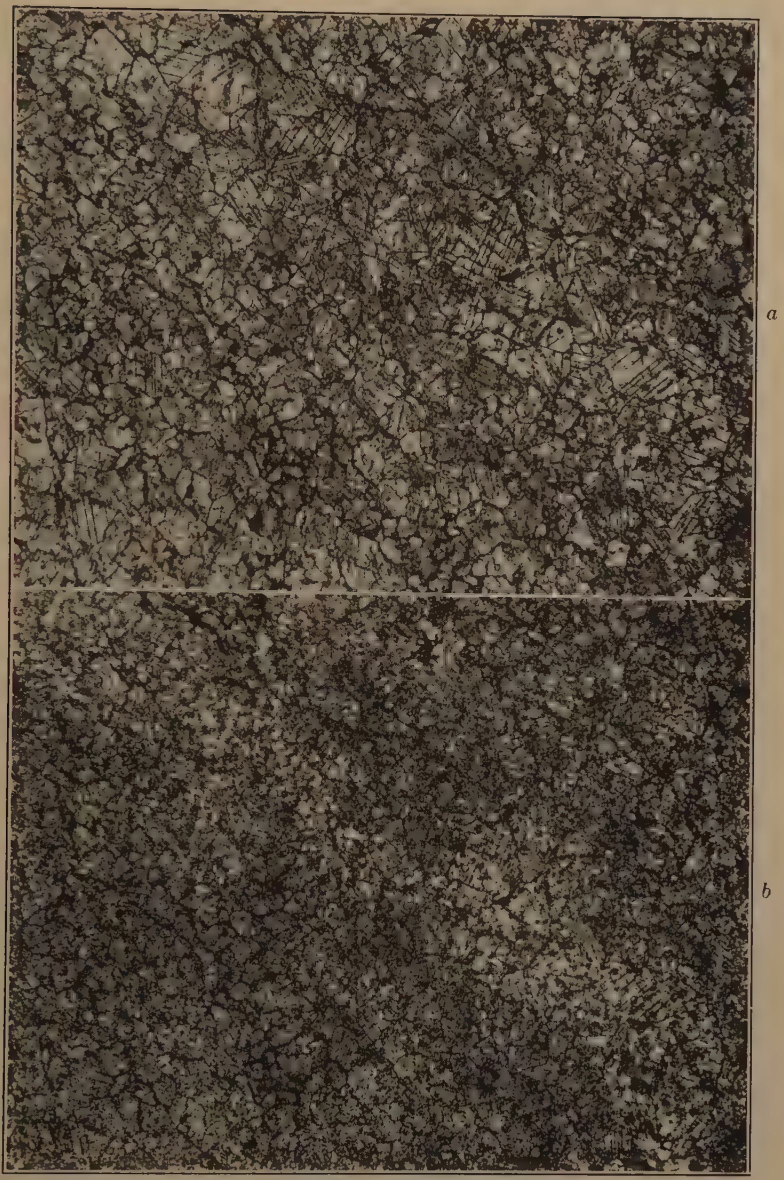

Fig. 5.—Jasperoid from Dobbins manganese mine. × 35.

a. Without crossed Nicols, showing preservation of the texture of the replaced carbonate rock, including that of a relatively coarse-grained veinlet. Carbonate cleavage also is well preserved.

b. With crossed Nicols, showing the much finer grain of the quartz as compared with that of the replaced carbonate.

west. Leached beds of the Shady formation, containing supergene manganese and iron oxides, are being mined (1938) from the north slope of the hill east of the Dobbins. Their gently arched structure indicates that at least the northern portion of the hill is anticlinal, the axis of the fold trending nearly due north and pitching northward. Another zone of faulting, indicated by jasperoid, ore minerals, and structural discontinuity, passes southwestward from workings just north of incline No. 5 through the larger Dobbins opencuts, and intersects the main ridge to the west.

In June 1938, operators of the Dobbins mine had reached depths of 115 and 118 ft. in two shafts south of the saddle. These were entirely in leached and oxidized Shady residuum. Earlier operations were carried to a maximum depth of 210 ft. without reaching any "hard rock formation."[6] This report of failure to penetrate the full thickness of the weathered residue of the Shady formation is borne out by the clay and weathered jasperoid on the dumps. The jasperoid, which consists of fine-grained quartz, preserves the texture and cleavage of the crystalline carbonate of which the rock originally consisted. In the process of weathering, supergene oxides of iron and manganese penetrate readily along the preserved boundaries and cleavage planes, emphasizing their presence in thin section (Fig. 5*a*). Between crossed Nicols, the rock is seen to consist only of quartz, mostly anhedral, and of much finer grain that the replaced carbonate (Fig. 5*b*). Veinlets of a relatively coarse-grained carbonate, having no sharply defined walls, had formed in the rock before silicification, for both matrix and veinlets were replaced.

Area 4

The manganese ores of the Aubrey area (Fig. 6) occur in the marginal portion of the Shady formation which blankets all but the crests of relatively low anticlines of the Weisner formation. The fissured and mineralized crest of such a low anticline, probably overturned, is represented by a remarkably straight zone, which includes the Aubrey and Stephenson open cuts. The fresh dolomite is covered by a deep mantle of thoroughly leached, ore-bearing residuum, but a few pinnacles of the rock have been exposed by erosion and mining. Northeast of the Stephenson cut, the pinnacles are veined by secondary calcite and quartz, and a pinnacle exposed in Little Aubrey cut contains limonite pseudomorphs after either pyrite or chalcopyrite. Silicification of the dolomite took place extensively, and subsequent leaching has left boulders of all sizes distributed throughout the residuum. A dump of these boulders, on the north rim of Aubrey cut, contains vein quartz intimately associated with the jasperoid, both containing ore minerals that are only partly weathered. A polished section shows pyrite, luzonite (pink enargite), tennantite, chalcocite, and covellite. Of these, only the chalcocite and covellite are known to be supergene. The chalcocite replaces tennantite, and is altered marginally to covellite. Lindgren[7] believes that pyrite-enargite veins are of hydrothermal origin, probably of mesothermal grade. The fact that hydrothermal manganese minerals and barite are known to occur elsewhere in such deposits offers the best provisional explanation of the source of the local manganese oxide ores and their characteristic barium content. Whatever its identity, the manganese member of this hydrothermal group is easily weathered, and may be alabandite or manganiferous carbonate. Its discovery, however, probably will await penetration of a vein or lode in the fresh dolomite beneath the oxides.

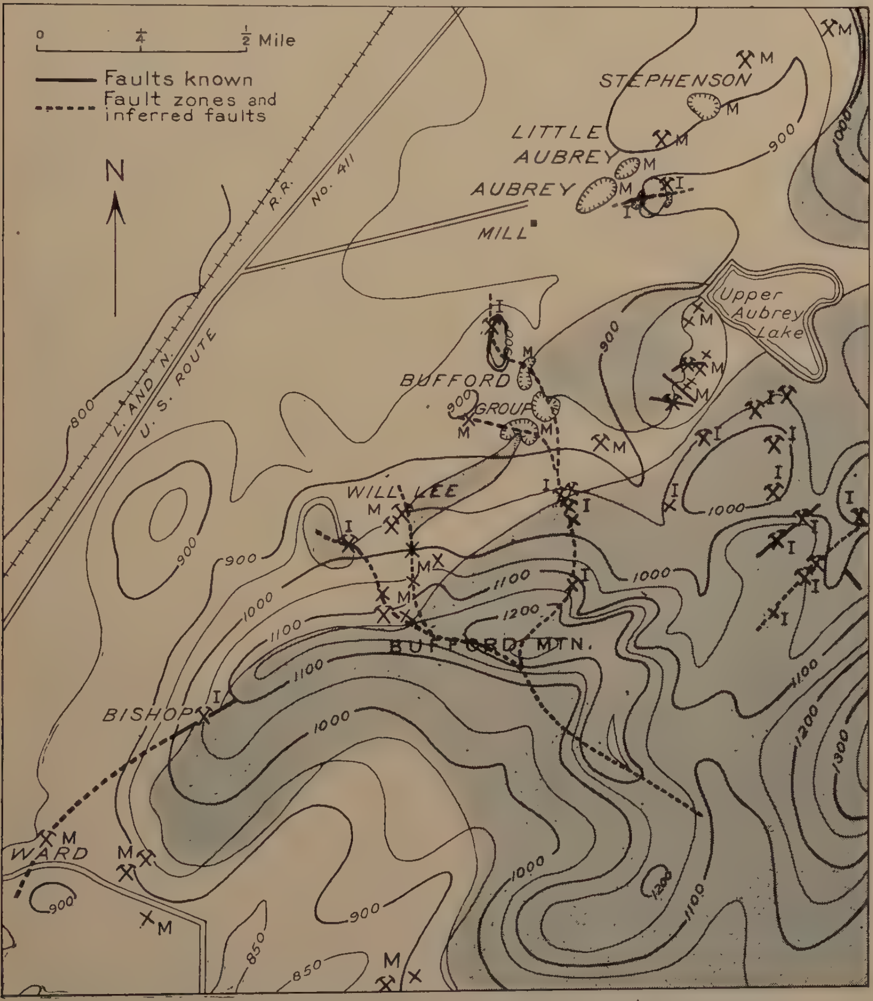

FIG. 6.—AREA 4, INCLUDING MANGANESE MINES OF AUBREY AREA. Shaded portion, Weisner formation; unshaded portion, Shady formation. Abbreviations as in Fig. 2.

Just east of the Aubrey cuts a knoll exposes the top of the Weisner formation in an anticlinal structure. The regularity of the fold is broken, apparently by faulting, and iron-ore mining has been carried on where breakage is evident. Specular hematite, which was mined with brown ore here, served as the full or a partial source of the brown ore. It is plentiful as float, some fragments containing vitreous vein quartz. On the south slope of this knoll, near Big Spring Creek, a gully exposed (1938) a considerable thickness of bedded low-grade muscovite schist of the lower Shady formation. A narrow layer of the schist, about one inch thick, consists of laminated, fine-grained specular hematite. This layer differs in no respect from the rest of the schist except in composition, and represents selective replacement of a narrow layer of the schist that may have been calcareous.

Zones of structural disturbance extend north and west from the top of Bufford Mountain (Fig. 6). A similar zone coincides with the northwest-oriented segment of a sinuous ridge that extends southeast from the peak. Owing to talus on the steep south slope of the mountain, it is not possible to determine whether breakage is continuous across the ¼-mile interval between, but it is considered probable. Nothing of commercial importance has been discovered along the zone southeast of the peak; however, where the magnesian limestones of the Shady formation were affected on the northwest side, ore minerals were deposited and later oxidized by weathering.

The north branch of fault disturbance was traced from near the top of Bufford Mountain through a series of brown iron-ore workings that extend down the north slope. Quartzite of the Weisner formation along this zone was considerably fractured and later impregnated with iron oxide during weathering, but no ore of consequence has been mined from it. In contrast, a large and irregular ore body was mined from the immediately overlying residuum of the Shady formation so that the principal workings of the series are those at the northern end. The only unweathered ore mineral found to date in these opencuts is specular hematite, and its active conversion into limonite is obvious. This zone of faulting on the north slope of Bufford Mountain trends slightly west of north toward the large opencuts known as the Bufford group, about ⅙ mile distant. The fault zone probably divides into two zones within this colluvium-blanketed interval. One appears to pass through the middle and north Bufford cuts, ending near the eastern extremity of an old iron mine where there are definite indications of faulting. Jasperoid containing pyrite partly weathered to brown ore was collected here. The other zone, if it exists, passes west through the south Bufford cut. The evidence for this interpretation lies in the fact that a prominent nose of quartzite of the Weisner formation is exposed in the south wall of the cut, but has no continuation in the north wall. This mass of quartzite probably is the sharp crest of an anticline, which, if projected across the cut, unquestionably would be exposed in the north wall.

It is believed that the quartzite exposed in the south Bufford cut extends beneath a thin veneer of colluvium nearly to the Will Lee mine, 0.3 mile to the southwest. A 50-ft. shaft about 200 ft. northeast of the Will Lee was sunk entirely in weathered quartzite, yet the adjacent Will Lee workings reached a depth of 160 ft., but did not pass through the weathered residuum of dolomite of the Shady formation. Thus it appears that a fault separates the formations here. In the light of foregoing examples, this fault and associated fissures probably controlled concentration of a large hydrothermal manganiferous deposit, which weathered to form the rich oxide ores mined here. About 0.1 mile southwest of the Will Lee mine, there are indications of considerable breakage in the south end of an older brown iron-ore cut. Between this iron mine and the Will Lee on the north, and the crest of Bufford Mountain on the south, there has been widespread prospecting and mining of manganese in dolomite residuum. As in other faulted and mineralized areas, jasperoid is abundant in these workings, and it is inferred that the breaks indicated at the Will Lee and the adjoining iron mine extend to the crest of Bufford Mountain where the Weisner formation dips northwest beneath the residuum.

Near the southwest end of semicircular Bufford Mountain, Shady dolomite is faulted against Weisner quartzite, and the Bishop deposit of brown iron ore has been mined from the fault zone. This fault trends toward the Ward manganese deposit, and evidences there of intense fracturing and inharmonious rock structures suggest that this deposit is controlled by the same or a closely related fault.

One-half mile south of Upper Aubrey Lake, two brown iron-ore mines about 500 ft. apart are situated on a vertical or very steep fault that strikes N. 50° E. These cuts reveal weathered sericite schist (which may possibly be infaulted schist, originally calcareous, of the Shady formation) dipping northwest on the northwest side of the fault, and quartzite of the Weisner formation dipping southeast on the southeast side. Both cuts are oriented parallel to the fault, and the ore has been mined out to the extent that only iron-impregnated quartzite remains on their southeast walls. Outcrops of quartzite adjacent to the southeast rims contain no iron minerals except scanty oxide stains, and the schists on the northwest sides of the cuts are also barren. Therefore, deposition of ore minerals clearly followed faulting. Bottoms of the cuts have been covered by slumping, but the writer found pyrite-impregnated quartzite that was taken either from the lower workings of these mines or from similar openings in this immediate vicinity, indicating that iron sulphide deposited in the fault zone probably was the source mineral here. An alternative but more unlikely explanation that deposition of the limonite was effected by descending meteoric waters would imply that the source mineral was present in the formerly overlying, but now eroded, Shady formation. Such a deposit, localized in faulted dolomite, would have been identical to those that are now exposed in the faulted lower part of the Shady formation, as described in this paper.

Conclusions

Deposition of ore minerals in the Cartersville district was controlled by two factors: (1) rock composition, it being clear that only carbonate rocks were extensively attacked by ore solutions; and (2) structure, it being equally clear that direct channels (principally faults and fracture zones) provided circulation to bring hydrothermal solutions in contact with the carbonate rocks. Specific examples are given to show the prevailing control of ore deposition by faulting.

Most of the faults are of the steep oblique type, and offsets are relatively small, ranging possibly from inches to a few hundred feet. They were developed by differential resistance to orogenic force in a zone of more or less highly compressed folds that involved the Weisner and Shady formations of Lower Cambrian age. These faults were mineralized where ore-bearing solutions could penetrate to the dolomite of the Shady formation, but the soft sericite schists of both the Weisner and the Shady formations undoubtedly plugged many faults as they were formed. The present ores are residual and oxidation products left from weathering of the hydrothermal deposits.

Ore deposits yet to be discovered in the areas discussed in this paper, which will be mostly extensions of known deposits, should be sought adjacent to the faults and broken zones described. Deposits elsewhere in the district were controlled similarly, but the features essential to locating and tracing the controlling structures are not often obvious in mine openings. Intensive areal study is necessary for a fuller understanding of genetic factors, and, therefore, more effective prospecting.

Acknowledgments

The writer is indebted to Mr. E. T. McKnight, of the U. S. Geological Survey, for microchemical work leading to identification of tennantite, and to Mr. Charles Milton, also of the Geological Survey, for supplementary chemical work in identifying this mineral. Mr. Milton also verified optical identification of strengite.

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Barite Deposits of Northern Nevada

By Vincent P. Gianella,* Member A.I.M.E.

(New York Meeting, February 1940)

Barite deposits are of widespread occurrence in Nevada but there are few producing properties; most of the latter are in northern Nevada. The production of the state is small at present—in the neighborhood of 15,000 tons annually—but is steadily increasing. The barite occurs in veins and also as replacement deposits in limestone. The bulk of the production has come from the replacement deposits. It is thought that the barite was deposited from rising hot waters similar to—and probably contemporaneous with—those responsible for some of the metallic ores of the state. This paper discusses only the deposits in northern Nevada.

The commercial mining of barite did not begin in Nevada until 1916 but although the production has been small there has been a rapid increase in tonnage during the past several years. Barite is widely distributed in the state and production comes from at least nine of the seventeen counties. Apparently this is not generally known, as only two counties are mentioned in a recent publication[6] dealing with barite. The increase in output is due largely to recently discovered barite deposits in northern Nevada. The principal production has come from the northern portions of Lander and Eureka counties; smaller amounts from Elko County. The discussion in this paper is confined largely to the deposits in these counties. Most of the producing area is tributary to the Western Pacific and Southern Pacific Railroads, whose tracks lie along the Humboldt River. Barite is known from other northern counties but so far the production has been small.

The output has come entirely from veins and replacement deposits, the latter largely in sedimentary rocks. In general, the barite from veins is white; that from the replacement deposits usually is dark gray to black, although some is light gray or white. Most of the veins contain sulphides and many barite-bearing veins have been worked for their content of base or precious metals.

PRODUCTION

The recorded production in Nevada to the end of 1938, according to the U. S. Bureau of Mines,[3] is 66,424 short tons, of which 57,157 tons

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[6] References are at the end of the paper.

were mined from 1932 to 1938. The marked increase during recent years is indicated by shipments of over 15,000 tons for 1938 and 1939, making the state an important producer of the Pacific Coast region. The location of the principal properties is indicated in Fig. 1.

DEPOSITS

A small tonnage of barite has been coming from the Eagleville mining district in southeastern Churchill County. Eagleville is a gold-silver mining camp about 10 miles north of Rawhide, virtually abandoned. The barite is trucked 64 miles to Fallon for shipment. The vein is 3 to 4 ft. wide and has a steep dip. The wall rocks are altered volcanics and, a short distance to the east, are intruded by granodiorite. Parts of the vein are quartzose and contain pyrite, argentite, free gold, cerargyrite and other minerals. At first, the mine was worked for gold and silver. The barite is white and some of it has a granular texture.

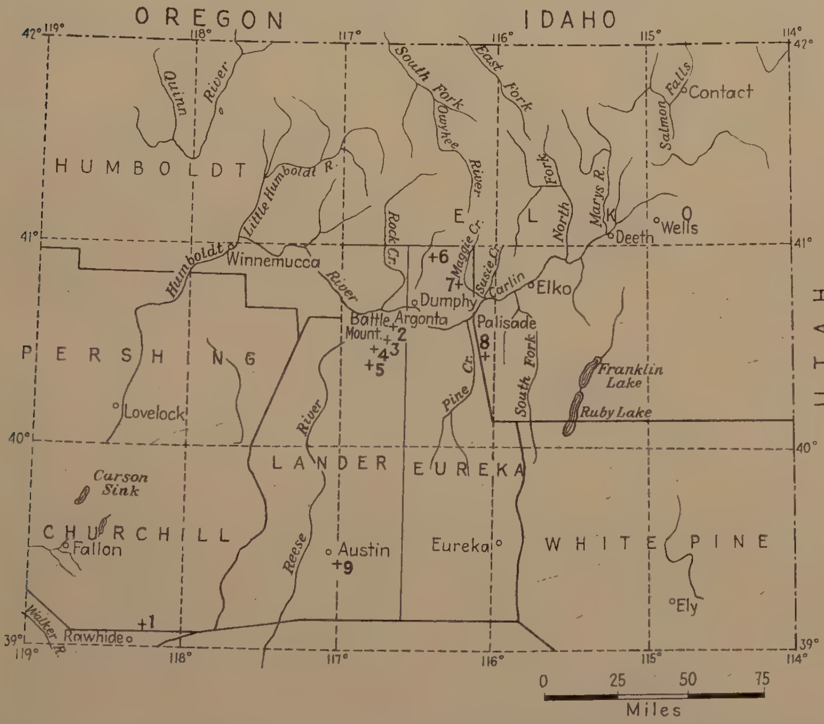

FIG. 1.—INDEX MAP OF PART OF NORTHERN NEVADA SHOWING LOCATION OF BARITE DEPOSITS.

1. Eagleville.
2. Nevada barite.
3. Valley View.
4. Bateman Canyon.
5. Hilltop district.
6. Simon Creek.
7. Maggie Creek.
8. Palisade.
9. Austin.

Barite is widely distributed in Lander County and there are several producing properties. Some of the more productive mines, and those of especial interest, are described in the following paragraphs.

The largest production in the county is from the Nevada barite mine, in the northern part of the Shoshone Range, about 4½ miles southeast of Argenta siding. The deposits are at the head of a canyon and near the western crest of the range. The elevation is 5900 ft.—1500 ft. above the Reese River Valley. At the larger (eastern) pit a good grade of barite is shown across a width of 80 ft., the vein has been traced for several hundred feet. About a mile to the north is a smaller pit exposing barite. It is probable that other deposits exist between these exposures. Several prospect pits in the neighborhood indicate the possibility of other producing properties. The bulk of the production has come from the eastern pit. The barite is dark gray, at places almost black, and contains occasional chert nodules and some narrow bands of shale. Most of these masses are readily discarded and the product is said to contain 90 per cent of barium sulphate and a small amount of barium carbonate. A higher grade could be produced if desired. The barite is blasted free, loaded on trucks with a power shovel and hauled to the Southern Pacific Railroad at Argenta siding. During mining operations some barite goes into the waste dump, from which it may later be recovered by a suitable plant. This deposit is the largest so far developed in Nevada. The barite has replaced a gray limestone. Siliceous shales crop near by. The country rock is limestone and shale with some quartzite and conglomerate. The strike is northwest and the dip averages about 30° east. The beds are somewhat contorted and in places have a much steeper dip. The eastern summit of the Shoshone Range is capped by basalt, which dips gently to the east and extends to Whirlwind Valley along the eastern base of the range. This Tertiary lava probably covered most of the adjacent region, as a small remnant lies upon the eroded edges of the Paleozoic sediments at the top of the ridge south of the eastern pit. Down the canyon to the north many basalt dikes cut the sediments. On the maps of the 40th Parallel Survey,[2] these sediments are indicated as of Carboniferous age.

Several miles farther south is the Valley View mine, immediately south of Slavin Canyon, at an elevation of 5900 ft., 14 miles southeast of Battle Mountain. The barite, about 8 ft. thick, probably replaces a bed of limestone, as it is overlain by about 2 ft. of black, carbonaceous shale and is underlain by a thin bed of similar shale. A considerable tonnage of dark gray barite has been mined. Shales and dark gray limestones crop near the mine, while farther away the section contains some conglomerate and considerable quartzite. A few fossils have been found in the barite, among which is the brachipod *Camaphoria*, considered by Wheeler and Muller[7] to indicate probable Pennsylvanian age. These sediments strike north and the dip is generally to the northeast at low angles. About 300 ft. northwest of the deposit is an outcrop of brownish limestone, which dissolves readily in weak acid to form a dark brown solution. Some brownish earthy material is found in vugs in the barite.

The overlying shale is removed with a power shovel and the rock mined by opencut methods. Little sorting is done. The shipments are said to run from 90 to 94 per cent barium sulphate and to contain a small quantity of barium carbonate.

Bateman Canyon, 15 miles south of Battle Mountain, contains deposits of barite from cream to white in color. The prospects are 3 miles east of Rock Creek at an elevation of 6850 ft. The barite replaces brownish limestone and contains small vugs of brownish, earthy material. The brown limestone is similar to that at Slavin Canyon. The production has been small but further development may reveal masses of barite of considerable size. The sediments are similar to those farther north. Near the workings some of the shale has been much silicified. The general strike is north with a dip of 15° to 25° to the west. One deposit of barite shows very irregular contacts with thin veinlets penetrating the surrounding limestone. The thin bedding of the limestone is well preserved in the barite. These relations clearly indicate replacement.

Barite is found in the Hilltop district about 19 miles south of Battle Mountain, where the Carboniferous sediments are intruded by granodiorite. There is a vein of quartz and barite in the Star Grove mine, near the head of Lewis Canyon, about 3 miles west of Hilltop. According to Emmons,[1] the vein has a northerly trend and dips gently to the west. It intersects the strata at a low angle. In places there is a 10-ft. width of nearly pure barite. In some parts of the vein are pyrite, galena, sphalerite and ruby silver. The mine was first opened and operated for its lead-silver content. A recently located barite vein in Lewis Canyon cuts beds of shale. The vein is reported to be 20 ft. wide.

A deposit of dark gray barite is in northern Boulder Valley northwest of Dumphey station. White barite is reported about 45 miles south of Battle Mountain but is said to be inaccessible. Many veins of white barite cut altered monzonite, about 10 miles southeast of Austin and one mile east of the Lincoln Highway. Vanderburg[5] describes the veins, which average 4 ft. in width. The barite is of good quality but the deposits are 100 miles from the nearest railway.

The possibility of further discoveries of barite in the Shoshone Range appears promising.

In northwestern Eureka County, about one mile west of the head of Simon Creek, is a deposit of white barite in veins cutting limestones and shales. This property is about 28 miles northwest of Carlin and a shorter distance north of Dumphey station, on the Western Pacific Railroad. The prevailing rocks are dark limestone, somewhat silicified near the veins, and dark, thinly laminated shales. The sediments trend N. 25°W. and dip 45° SW. These rocks have been regarded as Carboniferous in age.[2] The barite is in seams and veins, evidently fissure fillings and replacements. Some small bodies occur as irregular replacements of the limestone with some silicification of the adjoining rocks. The principal workings consist of a shaft with stopes opening to the surface. The barite is white with some staining by hydrated oxides of iron. In general the material appears to be of fair quality. The shaft was sunk on a vein that strikes N.85°W. and dips 45°N. In places the vein is 6 ft. wide. A considerable production has come from the mine. Some sorting has been done. Many prospect pits in the general region expose barite, indicating that it is to be found over a considerable area.

Near Simon Creek, a few hundred yards south of the Popovich homestead, there are veins of white barite that have been prospected by occasional pits and opencuts. The northern vein is 6 ft. wide where exposed in a pit, and strikes N.25°W. with a dip of 45°SW. At one place it contains a small mass of pyrite and a dark mineral, apparently an antimony sulphide. It is said that fire assay has shown gold in the sulphides. The more southern vein strikes N.50°W. and dips 70°SE. A width of 14 ft. is exposed in a trench. Here the hangingwall is much silicified. The prevailing country rocks are limestone and shale. The veins have not been developed sufficiently to indicate their possible value and the barite contains a considerable quantity of dark material.

About a mile south of Simon Creek there are two veins of white barite upon which little prospecting has been done. The veins exposed by the few pits are 5 and 12 ft. wide. The barite is white and in places contains inclusions of dark siliceous material. Development of these deposits may expose barite of good quality. The veins strike northwest and dip steeply to the southeast. An 8-ft. vein of white barite on Richmond Mountain is reported, about 3 miles to the south, but it is said to be inaccessible.

On the ridge west of Maggie Creek Canyon, about 11 miles northwest of Carlin, are deposits of white barite. According to Vanderburg,[4] barite is mined from a 10-ft. vein that strikes N.30°W. and dips 70°E. It is opened by adits and mined by the open-stope method. The product is trucked to Carlin for rail shipment.

From the nearly constant attitude of the veins in the region northwest of Carlin, it is probable that they are related to a fracture system of considerable extent. Further discoveries of barite in this region are to be expected.

White barite of good quality has been mined north of Deeth, Elko County. It was trucked to that station for shipment. Small shipments of brownish barite have come from a few miles south of Contact. A small production of white barite was made from a vein about 14 miles south of Palisade. The vein is enclosed in limestone on the mountain slope east of Pine Valley.

ORIGIN AND AGE OF THE BARITE DEPOSITS

Throughout the state there are numerous metalliferous veins, with either precious or base metals, in which barite makes up more or less of the gangue. The veins west of Simon Creek and the deposits in Bateman Canyon give clear evidence of replacement. The silicification of the surrounding rocks in the vicinity of many of the deposits, and the presence of witherite in at least two of the mines, suggests the deposition of the barite from ascending heated waters. The precious-metal content and the associated sulphide at Simon Creek, Eagleville, and the Starr Grove mine would indicate that those veins are of hydrothermal origin and strongly suggest that the other barite-bearing deposits may have been formed in the same manner. No evidence was found to indicate that any of these deposits were of meteoric or sedimentary origin. The ages of some of the metalliferous barite-bearing veins range from Jurassic to late Tertiary. The nonmetalliferous barite deposits may have a similar range. A more extensive study of the barite deposits of Nevada is in progress.

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DISCUSSION

(*John M. Boutwell presiding*)

R. S. EDMUNDSON, Charlottesville, Va.—It is this reviewer's opinion that silicification of the surrounding rocks and the association of witherite with some of the Nevada barite should be cited in a detailed description but not listed as criteria upon which a hydrothermal origin is based. It may be noted that the reviewer has given a detailed discussion of the evidence for the hydrothermal origin of certain barite deposits.[8]

The detailed report covering this study said by the author to be in progress will be of value to other geologists who have speculated as to the origin of other somewhat similarly occurring barite deposits.

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[8] R. S. Edmundson: A.I.M.E. *Tech. Pub.* 725 (1936), and Virginia Geol. Survey *Bull.* 53 (1938).

Mercury Deposits of Huitzuco, Guerrero, Mexico

By C. W. Vaupell,* Member A.I.M.E.

(Mexico City Meeting, November, 1936, and New York Meeting, February, 1937)

The Huitzuco mines lie in north central Guerrero, Mexico; production has been about 90,000 flasks of quicksilver since 1873. Near-surface ores fill extinct mud geysers and the deep deposits are chambered veins, stock-works in brecciated blocks, and replacements in limestone. The epigenetic minerals livingstonite, stibnite and sulphur occur in limestone, gypsum and dolomite through a developed vertical range of 260 meters. The deepest workings expose an increased amount of stibnite, which probably indicates that the lower limit of mercury mineralization is being approached. A resurgence of heat and water formed geysers over an extended area after the period of mercury mineralization. Mud geysers, which are situated, in the outcrops, contain the secondary mercury minerals, cinnabar and barcenite in the gravel and mud filling the vents. A 150-ton flotation plant is in operation concentrating stope fills that assay 3.0 kg. of mercury per ton. In one open stope, which is more than one hectare in area and 60 m. high, 150,000 tons are available.

INTRODUCTION

The Huitzuco mercury mines are of interest because of the unusual occurrence of ore in extinct geyser vents and the presence of several rare mercury minerals. Some of the deposits have typical characteristics of the telethermal zone and there is a gradation towards typical epithermal mineralization in depth. Halse,[1] Villarello,[2] Mactear[3] and Merrill[4] have described the geology and the early operations in the district, and Barcena[5] and Mallet[6] have described the rare mercury minerals, livingstonite and barcenite, found at Huitzuco.

LOCATION

The village of Huitzuco lies in the north central part of the State of Guerrero, Mexico, 27 km. (16.7 miles) east of Iguala, which is the largest and most important town in the area. Iguala is served by the Mexican National Railways and also by the Mexico City-Acapulco highway. The highway is surfaced from Mexico City to Iguala, a distance of 200 km. (124 miles) by road, and there is a fairly good, level, dirt road from Iguala to Huitzuco.

The elevation above sea level is about 1000 m. (3280 ft.). The climate is warm and very dry except during the rainy season, from June to

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[1] References are at the end of the paper.

September. Although the climate is warm, Huitzuco is not in the hot country proper and the natives are relatively free from the diseases of the tropical sections of Guerrero. The district has an abundance of potable domestic water and is well supplied with ordinary agricultural products.

The mineralized area lies in low, rolling hills 4 to 6 km. (2.5 to 3.7 miles) south of a high, rugged mountain range, which trends east-west. Flow rhyolites, trachytes and andesites with holocrystalline intermediate type intrusives occur high on the mountain ridge, some shale with limestone and granitic porphyry intrusives occurs in the foothills region, and limestone with gypsum occurs in the mineralized area.

History and Production

The first reported discovery of mercury at Huitzuco was made in 1873. One year later the mines were purchased from the discoverers and an operating company was formed. This failed, several reorganizations followed, and eventually the properties were sold, in 1885, to Romero Rubio, who was a prominent member of President Diaz' cabinet. Romero Rubio provided ample financing with good technical direction and a very active period of exploitation ensued. Additional ground was acquired, several shafts were sunk, and three Scott furnaces were built. By 1895, the Cruz shaft was 164 m. deep (534 ft.) and shortly after that the shaft was sunk to a depth of 215 m. (722 ft.). Eventually the stopes were carried to a depth of 20 m. (65 ft.) below the bottom of the shaft. The deposit outcrops 27 m. (90 ft.) higher than the shaft collar, so that it has been mined through a vertical range of 260 m. (877 ft.).

There is no production record for the period 1873 to 1885, but Halse[1] estimated that 30,000 flasks had been produced up to 1885 and that only 50 per cent of the mercury was recovered, because of the crude reduction methods used. The production from 1885 to 1906 was 22,116 flasks (762,998 kg.) produced from 236,983 tons of ore, or an average yield of 3.2 kg. (7.2 lb.) per ton of ore.

Romero Rubio died in 1896 and the estate administrators operated the mine until 1906. They then leased the properties to Lewis and Lujan, who operated on a small scale until 1910, treating unburnt ores cobbed from the Scott-furnace sinter and virgin ores gained from pillars and stope fills. The surface plant was entirely destroyed during the 1910 Revolution, the deep-mine workings were flooded, and the property was practically abandoned until 1925. Many of the surface pits had exposed ore when the exploitation stopped because of revolutionary troubles and the local miners treated this material on their own account. They used small retorts made of iron pipes and recovered between ½ and 1 ton of mercury per week for many years. These men made no attempt to extract the ore with any regard for future operations nor to develop new ore bodies systematically, so that the pits remain as monumental ruins of unchecked and undirected rugged individualism in mine operation.

The present owners of the property, Explotadora de Mercurio de Huitzuco, S. A., acquired the old Romero Rubio mines by purchase in 1930. The price of mercury dropped shortly after this company took possession and its full program has been delayed pending higher prices for mercury. The Cruz mine has been unwatered to the bottom of the shaft, some of the fills have been sampled and measured, the power line of the Mexican Light and Power Co. has been extended from Iguala to Huitzuco, four retort furnaces have been built and about 50,000 tons of ore have been burnt. A flotation mill to have a capacity of 100 tons per day is under construction and an extensive development program is being started. There are about 150,000 tons of sampled fills of ore grade in the mine, and large blocks of fills have not yet been sampled.

ORE DEPOSITS

The proven mineralized area is roughly 3 km. (1.8 miles) square. Not less than 90 per cent of the total production has come from the northern fourth and the remaining 10 per cent from the southern fourth of the area.

The ore deposits of the district are of two distinct types, genetically related but different in form and mineral content: (1) shallow deposits in which the mercury minerals occur in gravel and mud filling in extinct hot-spring and geyser vents; (2) deep deposits; blanket veins, chambered veins, stockworks in wide brecciated areas, and replacements in limestone.

The shallow deposits are locally known as *trojes*, which in Spanish means granaries, from their supposed resemblance to the round corncribs often used in Mexico. The complete ore troje is shaped like a wineglass or a tulip, with a long, straight, vertical stem and an enlarged top. The trojes are filled with a mixture of mud with gravel, which sometimes contains mercury minerals. The mud has a slight red and yellow stain of iron oxides and constitutes about 50 per cent of the mass. The gravels are predominantly gypsum with some anhydrite, limestone and dolomite, all of which occur in the immediate vicinity of the trojes. The largest pieces of rock are seldom more than 10 cm. (4 in.) in diameter and most of the gravel is well rounded.

The trojes usually occur in groups and often in series in straight lines. When the tops are joined, large shallow gravel deposits are formed. Fig. 1 shows the distribution of three gravel areas and the debris gravels in the valley floors, which may or may not be underlain in part by troje gravels. Certain limited sections only of the troje gravel areas are ore-bearing. Preliminary exploration, consisting of shallow pits and panning of surface material, indicates that 90 per cent or more of the troje gravels are barren. The known productive gravel areas shown on Fig. 1 have been mined to leave large open pits, of which there are 11 in the northern part and two in the southern part of the district. The largest pit, La Sorpresa, is 125 m. (412 ft.) long, 75 m. (247 ft.) wide and 15 m. (50 ft.)

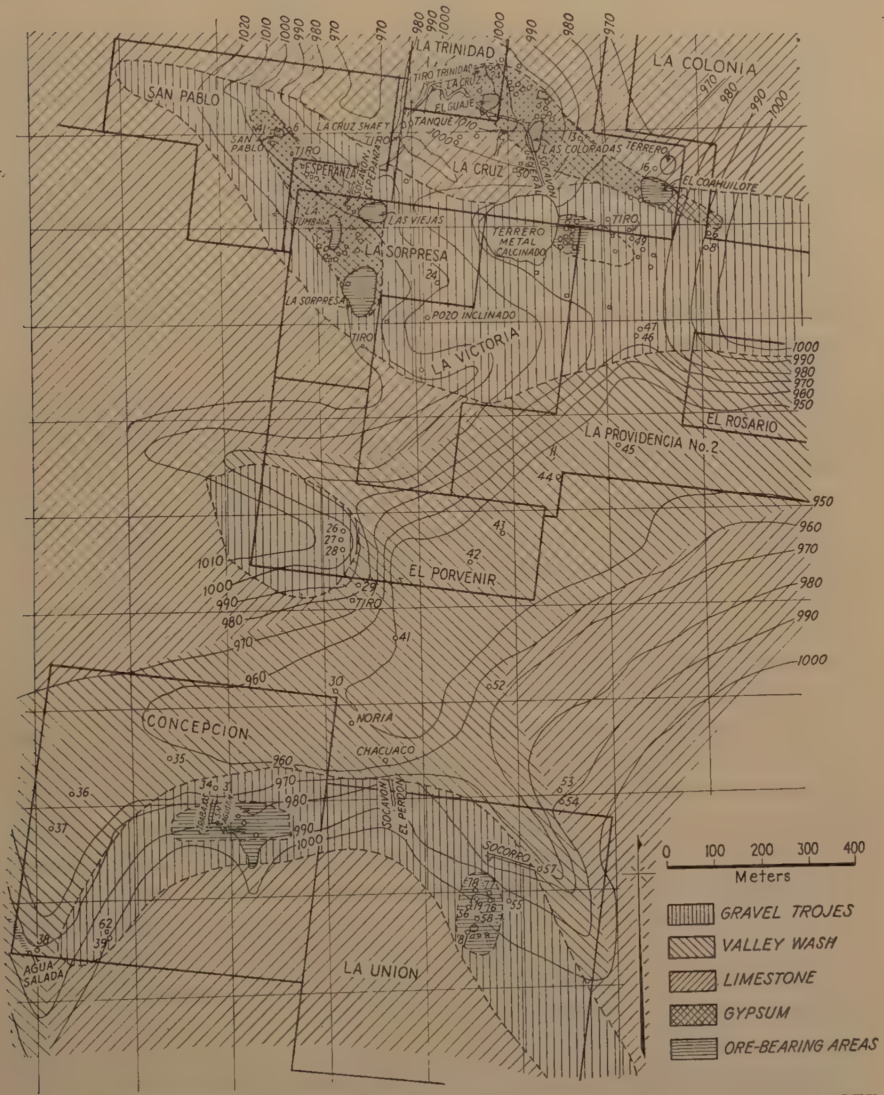

Fig. 1.—Distribution of three gravel areas and debris gravels in valley floors.

deep. The floor of the pit is broken by numerous, sharp, serrated ridges of country rock, which divide the whole into individual trojes. These funnel into stemlike chimneys, the largest of which attain depths of 50 m. (164 ft.) below the surface.

The chimneys are vertical. They vary in size, the smallest being seldom less than 10 cm. (4 in.) in the greater dimension and the largest individual chimneys seldom more than 10 m. (32.8 ft.) across. In places where the chimneys are in series along a fissure, they form composite chimneys or long, narrow channels. One of these is 50 m. (165 ft.) long and 6 to 15 m. (19.6 to 45.6 ft.) wide. The cross-sectional areas of the chimney stems decrease little if any with depth and because of their verticality and uniform cross section, it has been possible to use several of them as hoisting and ventilation shafts after the ore has been mined out. The sides of the chimneys show pronounced vertical channeling, which is uniform from top to bottom of the exposed sections. The stems appear to have grown from clusters of vertical pipes of 1 to 2 in. in diameter. Some of these enlarged and incorporated the smaller pipes to form the beautifully channeled sides with sharp, serrated edges and rounded grooves.

Underground development under a series of ore pits has exposed numerous chimneys of all sizes. In a few places the chimneys are open from their bottoms up to a bridge of large rocks on which the gravel and mud filling rests. Some exploration work has been done in several of these chimneys where ladders and manways have been put up as through an open raise, then the work has been advanced upward through the loose boulders into the gravel and mud horizon. No ore has yet been found in this work because the trojes have either been barren or else the previous operators have mined out the ore from the surface down. As a general rule, however, the chimneys are filled with mud and gravel throughout.

The chimneys do not bottom uniformly at the same depth. Some pipes terminate in massive country rock in a series of ellipsoidal chambers that are symmetrical in section, spaced one above the other and two to three times the cross-sectional area of the pipe section. The vertical channeling, which is a prominent feature of the pipes, is entirely absent in the bottom chambers, where there is usually a series of small horizontal rings or ridges on the sides of the chambers due to unequal erosion of the thin horizontal bedding of the wall rocks. Most of the chimneys bottom in mud-filled fissures, which vary in width from a few centimeters to several meters and which have every possible strike and dip. The fissures are not long, continuous structures, seldom being more than 50 m. long and pinching down to tight joint planes at the permanent water level.

Santiago Ramirez[7] visited Huitzuco in 1874, at which time the ores from the trojes were sorted into four grades: (1) 15 to 17 per cent mercury; (2) 8 to 9; (3) 5 to 6; (4) 3 to 4 per cent. Halse reported in 1895 that the ore from the trojes averaged 1 to 2 per cent mercury, and the small amount of ore that is now being mined from trojes averages 0.3 to 0.5 per cent mercury.

At some places, all the gravel in a group of trojes has been ore and the limits of the deposit are very definite at the troje walls, but at others the mercury minerals are confined to certain sections of a troje group and the limits of the ore bodies are economic. The Sorpresa pit was 200 ft. long in 1885. Since then lower-grade ore has been mined and the pit has been lengthened until it is now 412 ft. long. The pit has mercury-bearing gravels on several sides but these are below ore grade at present mercury prices.

The troje vents and basins undoubtedly had their origin in hot-spring and geyser activity. The rounded gravel with mud which fills the troje basins was either present during the last stages of geyser activity or was introduced mechanically after the geyser activities had stopped. Halse[1] believed that the filling of the troje basins was due to the denudation of the surrounding surface and the mechanical filling of the basins with rock debris which contained some livingstonite and stibnite. This view is not tenable because all the trojes would then be filled with gravels containing some mercury minerals, and also the valley wash immediately around the ore-bearing trojes should contain some mercury minerals.

Development work below ore-bearing trojes has invariably disclosed epigenetic mineralization and the writer believes that the troje ores are in place. During the explosive eruption stage of geyser activity it would have been impossible for any mud or small gravel to stay in the vent, but during the later quieter mud-geyser stage, country rock and ore fragments could have been plucked from around the mouth of the vent to form the enlarged troje tops. Movement of the rock and mud mass in these caldrons caused by escaping steam ground the softer rocks to form mud and rounded the larger and more competent rock fragments. Mud caldrons, which were situated in the outcrops of epigenetic mercury mineralization, developed into ore-bearing trojes. Other mud caldrons connected with the caldrons situated in the outcrops were mineralized through some mechanical mixing of the fills, and in large groups of trojes the mechanical mixing of the fills extended for varying distances from the ore source, always with a progressively lower mercury content away from the mineralization center.

In a typical troje area such as that in and around the Sorpresa pit, it is evident that the mercury content is definitely confined to a relatively small part of the gravel area and that there is a progressive decrease in the mercury content of the gravels away from certain centers. This is shown by the successively lower-grade ores gained from the Sorpresa pit as it has been enlarged. Thin seams of livingstonite ($HgSb_4S_7$) occur near the center of the Sorpresa pit in the serrated ridges that divide the pit into individual trojes.

The Baco group of trojes is a series of vertical pipes that do not have the typical enlarged tops. These trojes are on the top of a small hill and it is possible that the enlarged top sections have been removed by erosion. The mining of the ore from these trojes led to the discovery of the uppermost member of the series of ore bodies that have been exploited in the Cruz mine, and it is hoped that exploration under the Sorpresa and other similar pits will encounter mineralization channels similar to that found under the Baco trojes.

All the deep deposits have the same type of mineralization but they may be grouped into several classes according to their form:

1. Veins filling nearly vertical fissures.
2. Flat lenticular bodies, which follow some structural control such as bedding or flat fissures; blanket veins and chambered veins.
3. Irregular stockworks in wide, brecciated blocks.
4. Replacements in limestone.

Epigenetic sulphide ore has been encountered at five places in the district:

1. At Agua Salada, there is a nearly vertical vein, which crosses the country-rock bedding at approximately right angles.
2. At the Union mine, a flat lenticular body conformable to the country-rock bedding. The ore occurs below ore-bearing trojes.
3. At Conception mine, a thin (2-in.) seam of livingstonite dips 45° and connects into the bottom and sides of ore-bearing trojes.
4. Thin seams of livingstonite occur conformable to the bedding in gypsum pillars in the Sorpresa pit, 5 to 10 m. above the pit floor. The bedding strikes north-south and dips 6° east.
5. A series of ore bodies occurs in the Cruz mine. The three highest bodies in the series are blanket veins, more or less conformable to the wall-rock bedding; the fourth body is a chambered vein, which definitely cuts across the bedding; and the fifth and sixth bodies of the series are immense, irregular stockworks with some replacement of the limestone in a wide brecciated zone.

The Cruz Mine

A plan of the Cruz mine is shown in Fig. 2. The livingstonite ore was first discovered in mining the troje ores in the Baco group, which is a series of vertical pipes in two well defined lines, one with the direction N. 60 E. and the other N. 70 W. The lenticular ore body strikes N. 70 W. and dips 35° SW. conformable to the strike and dip of the block of gypsum country rock in which it occurs. It was encountered at depths of 10 to 30 m. in the trojes, of which some bottom in the sulphide ore horizon and others at lower horizons. The stopes in this ore body are now largely inaccessible but appear to have been about 45 m. (150 ft.) long on the strike, 15 m. long (50 ft.) on the dip and 2 m. (6.5 ft.) high. There are seams of livingstonite in the roof and ends of the stope but they are too irregular to be followed in exploration work. There is no sign of an outcrop at the projected continuation of the ore body to the surface.

The second ore body, the Espiritu Santo, was found by mining down the dip and following the irregular seams of livingstonite from the first lense. The second ore body was lenticular in shape, 45 m. long (150 ft.) on the strike and 18 m. (60 ft.) long on the dip. It was thin at the top and gradually opened out to a width of 2.1 m. (7 ft.) at the bottom, where it broke up into a number of small irregular seams, which also occur in the hanging wall and at both ends of the lense. The best ore is said to have been on the roof and in the upper, thinner part of the lense.

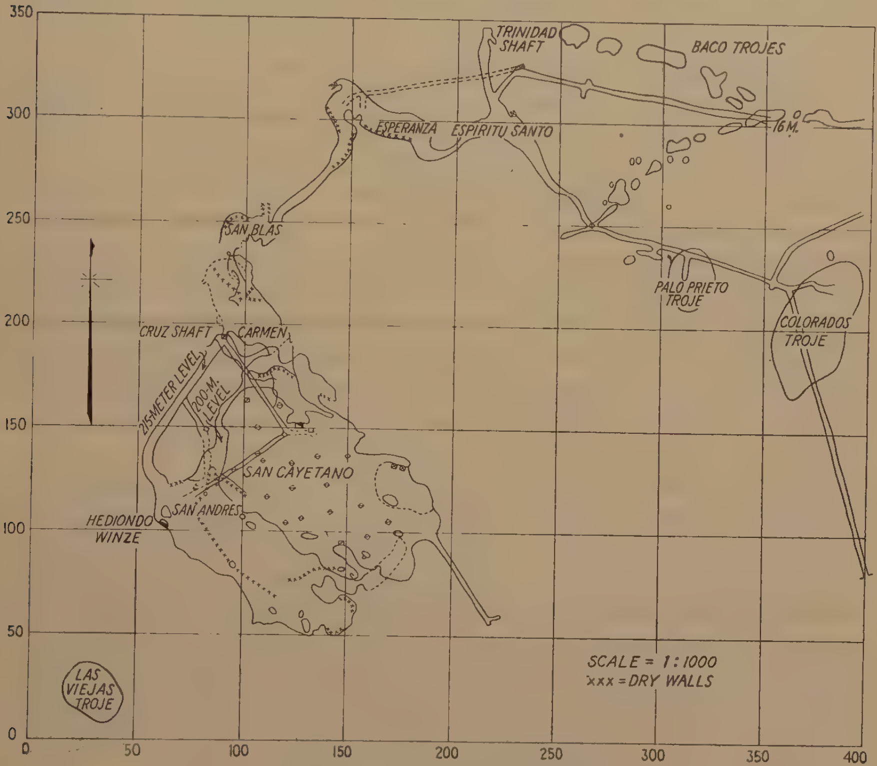

FIG. 2.—PLAN OF CRUZ MINE.

The third ore body was discovered by following ore seams into the footwall or floor of the Espiritu Santo stopes nearly vertically down a distance of 10 m. (33 ft.) where the seams joined and widened out into an ore body called Esperanza. This ore body has the form of two elongated convex lenses, joined at their edges and separated by a waste horse 8 to 10 m. (25 to 33 ft.) thick. The diameter of the top of the lenses is about 15 m. (50 ft.), the average strike N. 10 W. and dip 60° SW. The highest grade ore and the greatest thickness, 1.5 to 2.0 m., is said to have been on the hanging-wall branch. The ore was mined for 56 m. (185 ft.) on the dip.

An irregular winze of about 25 sq. m. (268 sq. ft.) in area was sunk 60 m. (197 ft.) below the Esperanza stopes, following thin seams of livingstonite which strike N. 50 W. and dip 40° SW., when a fourth ore body, San Blas, was encountered. The livingstonite seams are very irregular in width, varying from 1 to 5 cm., and they are seldom more than 2 m. long. Most of the seams are conformable with the bedding but there is some patchy mineralization in the floor and roof of the winze. Small ore bodies evidently were encountered in this development work, because the winze was widened at several places to three or four times its normal cross-sectional area. The San Blas ore body is reported to have had the highest grade ore encountered in the mine. The ore body is split into two chambered lenses, which crosscut the normal bedding of the enclosing limestones with the strike of N. 35 E. and dip of 50° SE. The highest grade ore occurred here in the footwall branch or lense, which was mined for a length of 20 m. (55 ft.) on the strike and 60 m. (165 ft.) on the dip, and for an average width of 4 m. (13 ft.). The upper chambered ore body has not been worked continuously; only at the top and at the bottom, where a part of the intervening horse is mineralized and a thickness of 15 m. (50 ft.) has been mined.

A winze about 30 sq. m. (328 sq. ft.) in cross section was sunk 10 m. below the San Blas stopes, following livingstonite seams, and a fourth ore body, El Carmen, was encountered. The Carmen ore body is an irregular pocket 50 m. (164 ft.) long, 25 m. (82 ft.) wide and 10 to 15 m. (33 to 50 ft.) high. The stope bottom is contracted to a cross-sectional area of 100 sq. m. and then the deposit opens out in the San Cayetano ore body, which was the deepest and largest of the Cruz series. The San Cayetano stopes are 120 m. (393 ft.) long, 100 m. (328 ft.) wide and open 30 to 50 m. (98 to 164 ft.) above the fills, which are 15 to 20 m. (49 to 82 ft.) deep above the water level and reported to be more or less the same depth below the water level. The roof of this open stope, which is approximately 1.2 hectares (3 acres) in area is slightly arched and stands without supporting pillars. A few blocks have fallen from the roof in the extreme southern end of the stope but in all other parts the roof appears to be solid, with no tendency to cave. A winze 45 m. (147 ft.) deep has been sunk through flat-lying gypsum beds below the present water level. No ore was exposed in this development. The waters encountered in the winze are heavily charged with hydrogen sulphide.

Extension beyond Cruz Mine

The series of ore bodies in the Cruz mine are a part of the mineralization that extends over a much wider area. Some brecciation with alteration of limestone to gypsum extends in a zone not less than 150 m. (465 ft.) wide from the Caohuilote pit to the Baco trojes, a distance of 700 m. (2296 ft.) with some probable extension beyond the explored limits. The strike is N. 20 W. in line with the series of trojes in this part of the district. There are no exploration workings to the limits of brecciation and alteration but it is the writer's opinion that there are no major faults limiting the zone. Throughout the area, there are large blocks of country rock which apparently are undisturbed, as they have the normal attitude of strike and dip; other large blocks have been tilted and others are intensely brecciated and recemented. No fault fissures with gouge or evidence of appreciable movement are encountered in the mineralized area but there are numerous tight partings and joint planes that cut across the bedding and recemented brecciated areas.

It is the writer's opinion that the brecciation resulted from upthrust. The force may have been exerted by an underlying intrusive rock mass, which has not been exposed in the Cruz mine workings, or it may have been caused by expansion due to the alteration of limestone to gypsum. An upthrust of relatively small movement in flatly dipping, bedded rocks with no great overburden may have lifted large blocks with little or no change in their normal attitude of strike and dip, with irregular brecciation around the periphery of the uplifted blocks.

The maximum amount of brecciation appears to have taken place about 200 m. below the surface, in the area of the San Cayetano ore body, below which an exploration winze has exposed a thickness of at least 45 m. (147 ft.) of flat-lying gypsum beds. Although the initial upthrust may have been vertically upwards, some adjustments along bedding planes would have tended to offset the resulting brecciation up the dip of the country rocks, towards the surface. The resultant structure is a series of brecciated blocks at depth, chambered lenses which partly crosscut the bedding at the intermediate depths, and lenses conformable with the bedding near the surface.

Ore Minerals

The fresh unaltered limestone country rock is a blue, fine-grained fetid variety, which has been classed as Cretaceous. Thin sections show numerous Foraminifera, which have not been identified. The wall rocks of the trojes and of the uppermost ore body of the Cruz mine is gypsum with little or no unaltered limestone, which occurs only around the periphery of the brecciated area in which the trojes occur. The country rock of the second ore body down from the surface at a depth of 45 m. (147 ft.) is essentially gypsum with some patches of unaltered limestone. The limestone shows a progressive increase with depth to the San Blas shoot at a depth of 125 m. (410 ft.) and from there to the 215-m. level there are about equal amounts of limestone, gypsum, anhydrite and dolomite. The 45-m. winze below the 215-m. level exposes only gypsum. The gypsum near the surface is white and granular, and at depth it is gray and fine grained.

Quartz, chalcedony or opal are not recognized megascopically in the ores from any horizon.

Livingstonite, stibnite, sulphur and a very minor amount of pyrite are the principal sulphide minerals encountered in the epigenetic ore bodies of the Cruz mine. Livingstonite ($HgSb_4S_7$) greatly resembles stibnite in general appearance but it is distinguished by its bright cherry red, waxy streak. This mineral occurs in the upper part of the mine in crystalline aggregates filling veinlets and seams, and in the lower part of the mine principally in metasomatic replacement of the limestone. The replacement has occurred unequally at a number of points in the mineralized mass, so that there are no definite ore limits or contacts of wall rock and ore. The replacements vary from a few disseminated livingstonite crystals at widely scattered points to mass replacement several meters wide. In the most intensely mineralized sections of the San Cayetano ore body, replacement of limestone alternates with filling of irregular fractures in the breccia blocks.

Crosscuts driven in the walls of the San Cayetano stope to facilitate the extraction of fills have encountered seams of livingstonite conformable with the country-rock bedding and vertical veinlike ore zones 1 to 2 m. wide where the mineralization has occurred in irregular, vertical fractured zones.

Little or no stibnite occurs in the upper part of the mine but several small veinlets of stibnite have been found at the 215-m. level. The occurrence of stibnite in the deeper workings points to the possibility that the lower limit of the vertical range of mercury mineralization is being approached at this depth.

The sulphur was deposited after the livingstonite and though often it occurs with the livingstonite, more often it occurs off to one side, in seams and incrustations on breccia fragments.

Guadalcazarite, a mercury sulphide similar to metacinnabarite, which contains up to 4 per cent zinc, has been reported in the Huitzuco ores. Tiemanite and onofrite with other rare arsenides and selenides of mercury, antimony and thallium have been reported present in specimens of Huitzuco ores, but none of these has been recognized in the petrographic studies made up to this time.

Just above where the water stood in the mine when the lower levels were flooded for 20 years, livingstonite is coated with bright red, secondary cinnabar stains around which there are clusters of acicular crystals of valentinite (Sb_2O_3) up to ½ in. long.

The ore minerals of the trojes are barcenite and cinnabar. Barcenite is a grayish black columnar or fibrous mineral with a greenish gray streak.

In its crystal habit it greatly resembles livingstonite, from which it probably is derived. Prof. J. W. Mallet[6] regarded it as an antimonite of mercury and lime. The surface of large lumps of barcenite is usually spotted with specks of bright red cinnabar. Barcenite occurs in clean pieces, which vary in size from sand grains to lumps weighing 3 or 4 kg. (7 to 11 lb.). These large pieces of barcenite are encountered irregularly throughout the gravels of the mineralized trojes. Most of the mercury in the trojes, however, occurs as minute specks of cinnabar and metacinnabar disseminated throughout the muds.

Probable Genesis of Deposits

Trachytic porphyry intrusives occur near the town of Huitzuco about 2 km. (1.2 miles) north and east of the Cruz mine, and one of the mine dumps in the Union mine area has some highly altered and decomposed material which appears to be a trachyte. No intrusive rocks have been encountered in the Cruz mine workings nor in the immediate vicinity of the trojes.

Whether brecciation occurred over an underlying intrusive to open the initial channelways is problematic. However, there was a circulation of hydrothermal waters, which probably occurred in several surges, the first of which altered portions of the limestone country rock to dolomite, and later there occurred the formation of gypsum on a large scale. Some slumping may have accompanied the dolomite phase of alteration, which was followed by expansion and swelling during the period of gypsum formation.

The hydrothermal waters circulated through wide brecciated areas in depth and worked their way around large unbroken blocks of country rock on their upward migration. After mineralization, there appears to have been resurgence of heat and perhaps also of water with intense geyser and hot-spring activity. The geysers, in the outcrops of the earlier livingstonite mineralization, reworked mercury minerals to form troje ore deposits. Other mud geysers not directly located in the outcrops developed similar structures, which are filled with barren muds and gravel.

Current Operations

The system formerly used in working the Cruz mine was to follow the ore in underhand stopes. Men and boys carried the broken ore from the working faces up to the empty stopes above, where the ores were hand-cobbed and sorted. The Scott furnaces were fed lump ore cobbed to about 10 cm. (4 in.) diameter. When high-grade ore was available, the fines from cobbing were mixed with clay to form round balls, which were sun-dried for several days and then burned. When the lower grade ores were being mined, the fines from sorting were stored underground behind dry walls.

The bottom of the shaft was usually 20 to 50 m. (65 to 165 ft.) above the underhand stopes, which necessitated a great deal of manual handling of the ore. Men carried the ore in wicker baskets that held about 25 to 30 kg. (55 to 66 lb.) each. These were carried on the shoulder, or on the back with a strap across the forehead.

When the surface plant was destroyed during the 1910 revolution and all work suspended, water filled the mine to a depth of 130 m. below the shaft collar. Ore thieves re-sorted the fills above the water level during this period and there is little or no ore left in this section. When the mine was recently unwatered to the bottom of the shaft, the fills in the San Cayetano stope above the water level were accessible for sampling. The stope was marked off in blocks and then 19 pits were sunk for sampling purposes. The pits were 1 sq. m. in section and sunk to the water level, 12 to 20 m. deep (38 to 65 ft.). The recemented fills were so well consolidated that light charges of dynamite were needed in sinking the pits. Floors were placed at the pit collars and the fills were piled up until one meter of advance was made; then the material on the floor was coned and quartered with shovels and cut down to a 20-kg. sample. Three hundred samples were taken in this manner and the average mercury content was calculated from the weighted average of the assays. An arbitrary 10 per cent reduction was made in the sample average for possible errors in sampling and assaying. The estimate was 187,000 tons of fills which averaged 2.4 kg. (5.3 lb.) mercury per ton. The fills in the San Blas and San Cayetano stopes have not been sampled but it is believed that some fills of ore grade will be encountered in this section of the mine; also, it is believed that fills of ore tenor exist below the water level in the San Cayetano stope, which is shown on old maps as being 15 to 20 m. deeper than the present water level.

About 50,000 tons of fills have been extracted during the past year. The fills are pulled by an electric scraper into chutes, trammed by hand to the shaft and hoisted in cars to the surface. About 40 per cent waste is sorted out, then the ore is crushed to 1 in., sun-dried and retorted.

The retort furnaces are built of twenty-four 10-in. black iron pipes cut into 7-ft. lengths. These are arranged in two tiers of 12 pipes each, supported at the ends by the walls of the furnaces, which are built of common red brick with firebrick used only in the fire boxes. Crude oil is used for fuel. The flue system carries the heat under the lower row of pipes, which are protected on their lower side by bricks, then between the two tiers and over the top tier, where the pipes are bare. Each pipe retort has its own condenser, consisting of a 6-ft. length of 3-in. pipe set on an incline down of 20°. A cross joint is set at the end of the condenser pipe with a 12-in. nipple placed from the cross into a water trap and a 6-ft. length of pipe connecting upwards into a large wooden box. The box of each furnace is connected into a flue system, at the end of which there is a small suction fan.

The furnacing of the ore is continuous. The time required for roasting depends on the richness of the ore treated and the location of the retort pipe in the battery but varies between 6 and 10 hr. The retorts are about two-thirds filled with ore, which is shoveled into the retort and then leveled with a scraper. A close-fitting sheet-iron plate is set inside and flush with the mouth of the retort, then this is sealed with mud, which hardens immediately. A small constant supply of air into the retort is furnished by the suction fan and a small hole in the sheet-iron end plate. The furnace operators test the charge by opening the retorts and taking out a small sample, which is dropped into water, crushed and then panned in a hornspoon. When no mercury minerals are seen in the hornspoon concentrate, it is assumed that the roast is complete and the retort is emptied and recharged.

The condensers are cleaned by scraping once each day with a flue cleaner. The accumulated muds from the water traps and condenser pipes contain about 40 per cent mercury. These muds are treated with lime to recover about 15 per cent of the mercury present. Very little metallic mercury is recovered at this stage, because of the formation of antimonides and sulphides. The condenser material mixed with lime is dried and retreated in small wood-burning retorts, where metallic mercury is recovered. Head assays and metallic mercury recovered indicate a recovery of about 65 per cent, which is increased somewhat by the mercury recovered in the semiannual clean-up of the flue system.

As mentioned before, a flotation plant to have a capacity of 100 tons per day is under construction. The laboratory mill tests have been made by David Segura, in Mexico City. His tests indicate that a very good recovery can be made by flotation to produce a high-grade concentrate. The mill was designed by Penhoel-Menardi Engineering Co. Ltd., of Los Angeles, and the construction is being done by the mine staff.

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The Teziutlan Copper-zinc Deposit, Teziutlan, Puebla, Mexico

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The Teziutlan copper-zinc deposit is supposed to be of late Cambrian or early Paleozoic age. The country rocks are a series of schists or phyllites, flat lying and in the form of a plunging anticline. The ore deposit occupies a single horizon in the schist for a known horizontal extent of 1200 meters. Along its strike occur four large lenses or ore bodies. These ore bodies occupy positions along the flank and extend to the crest of the anticline. The primary mineralization is in the form of quartz, pyrite, sphalerite, chalcopyrite and galena, with a few scattered silver antimonides. Quartz and pyrite form the mineralization between the ore lenses. In the ore lenses the sulphides appear as a massive, very fine-grained intergrowth of minerals. The intergrowth suggests a contemporaneous deposition of the heavy sulphides. The grain size, usually under 0.09 mm., makes the separation difficult and fine grinding important. The ore bodies were formed at great depth by solutions probably originating in the same basic magma that gave rise to the dolerite sills that are so common in their vicinity.

Introduction

The Teziutlan copper-zinc deposit is distinctly different from other ore deposits of Mexico in age and type. Previously stated to be pre-Cambrian in age, it is now quite generally supposed to belong to the late Cambrian or to the early Paleozoic period. Also, in contrast to the usual shallow-vein zone type of mineralization in Mexico, there is here exemplified an intermediate vein zone deposit of copper and zinc. So far as is known, the Teziutlan vein is unique in the history of Mexican geology and in a class by itself, its closest counterpart probably being the copper veins of the pre-Cambrian of Canada.

The Teziutlan district is in the extreme northwestern corner of the State of Puebla, Mexico. Teziutlan, the terminus of a branch line of the National Railways from Mexico City, is connected to the mine at Aire Libre by a 17-km. narrow-gauge railroad owned and operated by the Teziutlan Copper Co. Owing to excessive grades on this short line, Shay-geared locomotives are used for the transportation of concentrates and supplies.

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The topography of the district is rough and mountainous. From the high, mountainous plateau of central Mexico the terrain drops abruptly to the Gulf coastal plain just to the east of Aire Libre. This break is very sharp, almost scarplike in effect, and with the accompanying development of steep barrancas, canyons and the formation of numerous waterfalls. The latter offer an abundant source of cheap power for mining operations.

Aire Libre is at an elevation of about 4800 ft. Because of its situation, the rainfall is relatively high, averaging about 90 in. per year. The rainy season extends over the entire year and fogs are common. Although the climate is moist, Aire Libre is known as a very healthful camp.

The chief country rocks of the area are a system of phyllites and schists derived from both igneous and sedimentary formations. These rocks have been called pre-Cambrian in age, but this is very doubtful, judging from the appearance of the rock. A more acceptable age would be late Cambrian or early Paleozoic. Later igneous rocks are represented by dolerite sills, acid flows and intrusives, andesite flows and dikes, ash and tuffs. Relatively young sedimentary formations are exposed on the ridge to the south of Aire Libre, where there is a thick bed of agglomerate and the remnant of the original limestone capping, the latter being of Cretaceous age.

The Ore and Its Treatment

The copper-zinc vein was discovered about 1892 at what is now called the outcrop of the Aurora ore body. In about the same year the mine was worked on a commercial scale and the rich ore, averaging about 10 per cent copper, was shipped by muleback and railroad to the smelter in northern Mexico. So rich was the ore in copper that a profit of several million dollars was realized in a comparatively short period of time.

As the Aurora ore body showed signs of exhaustion a newer and deeper ore body on the same vein was discovered and developed. This was called the Cometa ore body and it was followed by the Volcan and, the last and deepest to be discovered, the Minerva.

With the depletion of the Aurora ore body and the opening of the deeper sections of the vein, it was found that the copper and zinc content of the ore changed; that with increased depth the copper grade decreased and the zinc content increased. For this reason the ore could no longer be profitably shipped and a smelter with blast furnace was built on the property in 1906. The smelter served for several years, until the zinc content increased to such a degree that the installation of a roaster was necessary.

About this time—1912 or 1913—a mill was built using combination tabling and bulk flotation with more or less successful results. However, the continued change in the character of the ore and decreasing metal prices finally forced the mine to close down in 1917.

In 1925 selective flotation made it possible to treat the ore profitably until 1931, when low metal prices forced a complete shutdown. Mining operations were at a standstill until the mine was reopened in 1936.

No figures are available for the total production for the years preceding 1925. The period 1925 to 1931, however, showed a total production of 325,000 tons of ore, the amount of copper in concentrates produced being 17,800,000 lb. Over this same period of time the average grade of ore was as follows: Au, 0.06 oz.; Ag, 2.5 oz.; Cu, 3.2 per cent; Zn, 12.0 per cent; Pb, 1.20 per cent.

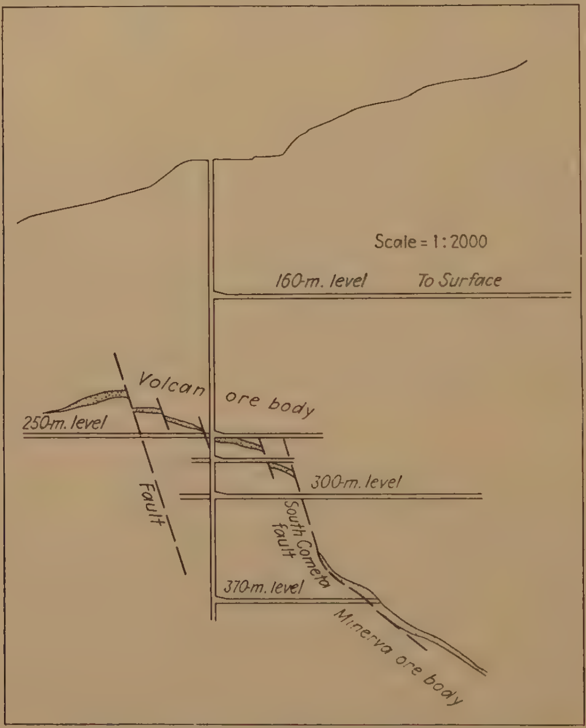

Fig. 1.—Section through Minerva shaft.

Present mining is confined to the Minerva ore body. Access to the Minerva is by means of the Cometa tunnel, or the 160-meter level to the Minerva shaft and down to the 370-m. level (Fig. 1). At this level, a 100-m. crosscut intersects the ore body. Because there is a solid hanging wall, very little timbering is necessary, the support being furnished by occasional pillars.

The treatment of the ore is entirely by the selective flotation method. The ore is crushed and ground to 95 per cent minus 200-mesh size.

From the classifiers the pulp passes through the flotation and filter section. Three concentrates are made: copper, lead and zinc.

PETROLOGY

The principal country rock of the area surrounding Aire Libre consists of a series of phyllites and schists. For the sake of convenience, these will hereafter be referred to simply as schists. These metamorphic rocks represent an original series of sedimentaries intruded by dolerite sills and acid porphyries and the entire series then highly metamorphosed preceding the period of ore deposition, which probably occurred at great depth under conditions of high temperature.

Following metamorphism and ore deposition came a long period of uplift and erosion, which was followed by the deposition of thick agglomerate. Above this agglomerate was then deposited a thick bed of massive gray limestone of Cretaceous age. About this same time there was renewed igneous activity, as shown by the presence of a trachyte neck, acid intrusives as dikes, etc., and also by beds of tuff. Following the limestone deposition came another period of uplift and erosion accompanied by the extrusion of andesitic lava and a still later bed of ash. The andesites and ash now occupy the hollows in the old land surface and lie below the horizon of the limestone capping of the ridge to the south of Aire Libre.

During one period in the development of the mine it was thought that the location of the ore was controlled by a dolerite sill contact with the country-rock schist. A petrographic study was undertaken of the various metamorphic rocks in an effort to prove the theory and to formulate some simple line of development of the mine. Because of the extreme degree of metamorphism, the dolerite sills and original sedimentaries cannot be distinguished without the use of the petrographic microscope.

The result of this study was the classification of the ancient schists into three groups: (1) meta sedimentaries, usually phyllitic; (2) meta dolerites, usually phyllitic, medium to basic intrusives; (3) meta porphyries, usually phyllitic, medium to acid intrusives.

The meta sedimentaries, as noted, are of sedimentary origin, have no definite set of characteristics, occur in a variety of colors and with an extremely variable composition. They are usually found as large blocks within the dolerite masses or sills and in a highly shattered state.

The meta dolerite is a medium to basic intrusive rock. In the hand specimen it appears as a dark, greenish, fine-grained rock with a phyllitic to massive structure. In thin section it is characterized by an abundance of oligoclase feldspars, which readily distinguish it from the other rock types of the area.

The extent of the dolerite has never been determined because later surface flows have covered a great deal of the former land surface.

As far as known, the footwall of the dolerite occupies a position along the base of the range of hills south of Aire Libre and, following the strike of the sedimentaries, continues east in the general direction of Teziutlan. The hanging-wall contact has not been delineated, owing to the overlying flows and ash beds, therefore the thickness of the dolerite is unknown. The horizontal extent also is unknown, although a similar section is shown at the Guadalupe mine, 6 miles west of Aire Libre.

In the upper ore bodies the dolerite is in the form of a large intrusive body containing isolated blocks of the intruded sedimentaries. Reaction rims and contact zones have been found in many places along the contact of the igneous rocks and the sedimentaries or the schists. The dolerite evidently was intruded in the form of sills of various dimensions.

The Minerva ore body shows two small dolerite sills in the footwall cut by the 370-m. level crosscut from the Minerva shaft. One is about 10 m. wide and the other about 15 m. Between the two lie highly altered phyllites. The lower dolerite sill shows highly altered contact zones, on both hanging wall and footwall, each about 30 cm. wide.

In hand specimen, the metaporphyry has a brownish color, which, while never very prominent, is, nevertheless, very distinctive. The metaporphyries occur sometimes massive and at other times with a very well developed schistosity. The thin sections of the porphyry show large phenocrysts of orthoclase feldspar in a very fine, even-grained groundmass. Quartz usually is present and epidote only near the dolerite contacts.

Apparently the metaporphyries make up a large portion of the exposures in this area of Aire Libre. The best and most certain exposure is in the footwall of the Aurora and Cometa ore bodies. In other localities they are distinguished with difficulty from the other metamorphic types. Originally these metaporphyries were probably acid flows.

Among the later intrusives, perhaps the most widely distributed are the acid dikes and flows, of which the most common variety is the aplite and bostonite.

The bostonite dikes are the most important locally, because they have cut the vein in many places. These dikes are light cream to gray or brownish red in color and rather fine in grain. They range in thickness from one meter to four or five or more. Interest in these dikes lies in the fact that although some, at least, are certainly later than the ore bodies, some facts indicate their presence before the formation of the ore bodies. This latter suggested that the dikes acted as localizers of the ore and that they were to be followed as a guide to the ore.

The bostonite dikes appear to occupy no particular zone and to have no definite strike and dip. At various points, the dikes cut the ore bodies at a very small angle. Other exposures show almost vertical bostonite dikes cutting the ore bodies at almost a right angle. In general the strike is more or less the same as the strike of the schist.

Many instances have been cited in previous reports, wherein there is a marked difference in the mineralization on either side of a dike. The zinc content may be much higher on the hanging-wall side than on the other. Also, the ore body may differ markedly in thickness on either side of a dike; and whereas the vein material on one side may be classed as ore, on the other side of the dike it may be too low in grade to be worked profitably.

The two features last mentioned might possibly be interpreted as evidence that the dike was first and that it was followed by the introduction of the vein material. In this case the dike may have acted in the manner of a dam, partly shutting off the solutions from the sections on the other side of the dike. However, if this theory were true there would undoubtedly be some alteration of the dike parallel to the ore contact. To a minor degree there have been noticed small disseminated pyrite specks along the edges of certain of the dikes, but not of a type or form to suggest that they were the result of alteration of the dike by the vein. A thin section of a selected chip of the bostonite showed a fresh and unaltered rock, entirely devoid of alteration except perhaps a slight alteration occurring during the last phase of cooling within the dike itself. There is, however, a definite banding in certain sections of the dike walls, which resembles flow structure in a viscous magma.

Alteration of the vein material or schists adjoining the dikes cannot be observed as a prominent feature, thus suggesting the possibility of the intrusion of a rather dry and viscous magma.

The difference in size and mineralogical content of the ore bodies on either side of the dike can best be attributed to the existence of a pre-dike fault, which acted as a barrier dam to the hydrothermal solutions that formed the ore. After ore deposition came the period of intrusion of trachyte, aplite and bostonite dikes, some following along these pre-mineral faults for part of their extent at least.

STRUCTURE

The structure of the area of the ore bodies is rather simple in general. The schists have a general strike of east-west and a south dip in the Aurora or most easterly lense. This east-west strike continues west through the Cometa ore body to the Volcan, where it begins to turn more northeast and southwest. The dip of the schist is from 25° to 40°. The ore bodies or lenses apparently are concentrated on the crest of a gently plunging anticline or on the south flank of this anticline. At a later period the ore bodies were cut by numerous faults; these have offset them as much as 50 m. in some places, but the average displacement is only 4 to 5 meters.

Throughout the extent of the three upper ore bodies faulting has been a factor of considerable importance in the mining operations. The ore bodies along the vein have been cut by many faults, both normal and reverse, although the former are by far the most numerous and have caused the greatest displacement.

As a general rule the strike of the faults is parallel to the strike of the aforementioned plunging anticline, approximately NE.-SW. The dips of the faults vary considerably from place to place but usually are steep, 60° to 80°. Locally the faults may be very flat, 20° to 30°.

The presence of both normal and reverse faults has provided a continual source of difficulty in following the vein, but this feature is partly offset by the fact that most of the faults have good fault surfaces, and usually indicate clearly by the drag the direction of the movement. This is especially true of the larger faults.

Little mention is made of several cross faults, as in the majority of instances they have given rise to only a slight displacement. At a number of places in the orebodies, where the cross faults occur along the edge of the ore lenses the ore body has become very narrow and low grade. Consequently, little effort was made to go beyond the limiting fault in search of the displaced segment.

The deepest ore body apparently is outside the zone of greatest readjustment, and the small faults are almost entirely lacking. The Cometa fault, with a displacement of some 50 m., cuts the top of the Minerva ore body, follows along the footwall of the vein and then, apparently steepening its dip, again leaves the vein.

In addition to the post-mineral faults, there is the possibility of the presence of a set of pre-mineral faults, as mentioned in the discussion of the bostonite dikes.

THE ORE BODIES

The ore deposit of Teziutlan is in the form of an extensive flat-lying, slightly mineralized zone which, at intervals, widens into large elliptical lenses of massive sulphide ore. Throughout the extent of the deposit, there is apparently one certain horizon in the schist, which has been the host rock to the ascending hydrothermal solutions carrying the sulphides. Just what particular characteristics have accounted for the mineralization being confined to this single zone is at present unknown.

The mining operations have exposed four lenses of ore (Fig. 2), ranging in size from 200 to 300 m. in length, 100 to 200 m. in width and averaging 2 to 2.5 m. in thickness. The entire deposit has a known horizontal extent of 1200 m. and a depth of 500 m. measured vertically. Between the lenses the ore body usually consists mainly of silicified schist, quartz and pyrite.

The filling consists of a complex intergrowth of massive sulphides; the minerals being pyrite, sphalerite, chalcopyrite and galena. Present also to a limited extent are tennantite, argentite and tiny specks of an unidentified mineral, probably an antimonide of silver.

There has been a gradual change from the upper to the lower lenses in the copper-zinc ratio, which has been reflected in the method of development of the mine. The Aurora ore body, the only one outcropping, carried a high percentage of copper and a low percentage of zinc. This ore lent itself readily to smelting operations. Then, contrary to the usual orderly sequence of mineral deposition, the copper content decreased and the zinc increased. This change of mineralization with increased depth gives the appearance of a so-called telescoped ore body formed during a time when the temperature was increasing. This would tend to reverse the usual order of deposition.

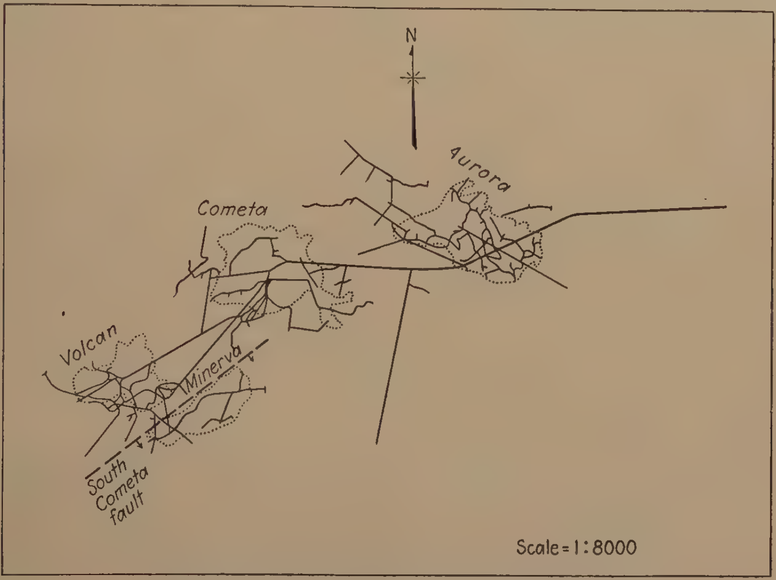

FIG. 2.—POSITION OF ORE BODIES, TEZIUTLAN.

The ore minerals occur as a massive replacement of the schist country rock. Banding is rare. There is banding along the walls of the vein, but it is the exception rather than the rule. Alteration of the wall rock is not extensive and usually does not extend more than 0.5 cm. from the vein contact.

The size of grain of the ore minerals varies slightly from the center of the lenses to their borders, but the average grain is about 0.074 mm., or −200-mesh screen size. Crystals of pyrite are common but the other sulphides do not occur except in the massive form.

Vugs are lacking. Also lacking are any definite, distinctive high-temperature minerals. In most places the wall rock has been only slightly altered. The ore lense may pinch or swell with remarkable rapidity, all of which seem to indicate ore deposition under conditions of moderate temperatures and pressures. Therefore the deposit can probably be classed as in the intermediate zone, although presenting certain features of the deep vein zone.

MINERALOGY

The groundmass of the ore is composed of quartz and pyrite, both highly fractured, broken and replaced by later sulphides. This brecciation took place previous to the later sulphide deposition.

Sphalerite is the most abundant heavy sulphide. It occurs in a massive form replacing the pyrite, and filling cracks and fractures in the broken quartz. In the center of the ore body the grain size may be as much as 0.05 mm. in diameter, but this is rather unusual. The assays and mill recovery, as well as the color of the sphalerite, indicate a relatively pure mineral.

Accompanying the sphalerite is chalcopyrite, which occurs as a fine intergrowth with the sphalerite. Some specimens show a definite replacement of sphalerite by chalcopyrite. The grain size of the latter is well under 0.074 mm. average. Many specimens show only tiny specks of chalcopyrite scattered through the sphalerite as a result of unmixing of a solid solution. In addition to the chalcopyrite that occurs with the sphalerite, there are occasional segregations of chalcopyrite in quartz, which apparently belong to a slightly different period of mineralization.

Galena occurs in small quantities, usually about 1.20 per cent per ton. It is in the form of tiny grains intimately intergrown with the chalcopyrite and sphalerite. The grains usually are no more than 0.02 mm. in size. They also apparently represent a product of unmixing. Some sections show the galena as replacing the sphalerite or chalcopyrite, but the most common type shown is that of an intergrowth of the minerals, all of the same age.

Other minerals present include tennantite and perhaps another of the antimonides. Certain grains of galena grade into argentite toward their boundaries. This relationship is very apparent from a differential reaction with acid. Most of the silver is presumably in the form of argentiferous galena.

ORIGIN OF THE DEPOSIT

The mode of origin of the copper-zinc ore and the source of the metalliferous solutions are open to question. The source of the solutions may be assumed to be some underlying, deep-seated magma. The hydrothermal solutions rose until they encountered a zone in the overlying schists which, because of high permeability or its soluble character, etc., formed a channel. Along this channel the solutions or gases rose and spread out until, reaching some dam—say the crest of an anticline—under conditions of favorable temperature and pressure they deposited their load as massive replacements of the schists.

Secondary enrichment is practically lacking in the deeper ore bodies. Although the old Aurora or upper ore-body workings are inaccessible, and no mention is made in older reports of secondary enrichment, it is to be suspected from the richness of the ore mined that the ore had been enriched to a great extent. In addition to concentration of the copper, it is very likely that the zinc had been removed, because of rapid erosion and the excessively moist climate.

SUMMARY

The Teziutlan copper-zinc deposit is supposed to be of late Cambrian or early Paleozoic age. The country rocks are a series of schists or phyllites, flat-lying and in the form of a plunging anticline. The ore deposit occupies a single horizon in the schist for a known horizontal extent of 1200 m. Along its strike occur four large lenses or ore bodies. These ore bodies occupy positions along the flank and extend to the crest of the anticline.

The primary mineralization is in the form of quartz, pyrite, sphalerite, chalcopyrite and galena, with a few scattered silver antimonides. Quartz and pyrite form the mineralization between the ore lenses. In the ore lenses the sulphides appear as a massive, very fine-grained intergrowth of minerals. The intergrowth suggests a contemporaneous deposition of the heavy sulphides. The grain size, usually under 0.09 mm., makes the separation difficult and fine grinding very important.

The ore bodies have been formed at a great depth by solutions probably originating in the same basic magma that gave rise to the dolerite sills, which are so common in their vicinity.

ACKNOWLEDGMENTS

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Geological, Chemical and Physical Problems in the Marble Industry

By George W. Bain,* Member A.I.M.E.

(New York Meeting, February 1940)

Some problems concomitant with commercial exploitation of marble are presented as examples of interesting, useful and profitable fields for application of scientific knowledge. The marble industry is only one such field and is selected because its varying new aspects are familiar to the author. However, what is true for marble is equally so in principle for many industrial minerals.

The problems of any stone industry are to maintain markets, create new outlets for stone already in demand, and develop varied uses for varieties that are not so popular. Here the geologist has a different role from most of his colleagues in metal mining. The producing branch may ask about the expectable variation in thickness or size of a deposit as development proceeds. The stock department may call for the available amount of a given type of stone before accepting a large order. The sales force requires data on the use for stone from certain parts of deposits in order to divert grades to the most suitable use. The service department wants defects rectified and the cause determined to avoid recurrence. The mills want data on durability and cutting quality of abrasives. The geologist occupies no special department; he is on general call, as may be illustrated by a few types of problems that may be classified as: (1) dominantly geological in character, (2) dominantly chemical in character, (3) dominantly physical in character.

Geological Problems

The geological problems deal almost exclusively with the size of blocks. Size across the deposit is limited by thickness of individual beds, and along the strike by the space between crosscutting joints. Frequently the vertical depth of a block is reduced by exfoliation shells arising from spontaneous expansion. All these factors require consideration in developing a deposit to fill an order.

Thickening of Marble Beds

The limestone beds that became the marble deposits of the northern Appalachians and of the Yule locality in Colorado were seldom homo-

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geneous through 2 ft. of thickness. Locally they are swelled out to 60 ft. by glacierlike flow of the stone. Locating these swelled sections is a strictly geological problem.

Flowage at High Street in Brandon, Vermont, has concentrated the marble into the bottom of a syncline, where it is 50 ft. thick, and thinned the flanks and crests of adjacent anticlines until little stone of the marble bed remains. At Pittsford Valley, flowage has contracted the area of the less competent beds along an axis inclined 65° southward in the bed and thickened them along an east-west axis normal thereto. (See Fig. 1.) Accordionlike shear folds appear in the more competent and distinctive beds. Flowage has caused some remarkably thick deposits at Proctor and West Rutland, 7 to 15 miles farther south.

Deformation between West Rutland and Danby, Vermont, is along three to five thrust faults; flowage structures, so essential to thickening, are lacking. The flowage or "distributed shear" type of movement suitable for thickening of marble occurs only at the north and south ends of the highly thrust belt; there only have thick deposits been found.

Similar marble beds at the two ends of the thrust belt differ in most physical properties, owing in part to the type of folding. All northern deposits have flowage parallel to the axial plane of the folds (shear folding). All southern deposits have flowage parallel to the bedding planes in the deposit (flexural folding).

Soundness, or Freedom from Joints

Thickness of uniform marble is insignificant where numerous cross joints reduce the length of blocks along the strike, disrupt the regularity in quarry plans and render the locality worthless as marble land. Joints are of two sorts; the first variety is inherent in the rock for geologic ages, the second group develops spontaneously as the stone is quarried.

Primary joints occur in groups and are identified by associated weathered minerals. Most lowlands in the marble belt follow jointed zones, which allow ground water to enter and promote decay. Most commercial marble comes from hills where joints are rare.

All freshly exposed rock is believed to be under stress imposed when tectonic forces produced the thickening. The stress is almost horizontal at Pittsford Valley and approximately vertical at West Rutland, and causes rupture where channel cuts permit extreme inhomogeneous strain. Cutting the west channel first at Pittsford Valley isolates the relieved rock adjacent to the face of the hill from the highly stressed rock behind (Fig. 1). Deposits in exposed hills like the shallow part of Pittsford Valley quarry No. 7 at Danby, Vt., and the Yule, Colorado, have had all stress of destructive magnitude dissipated slowly during the years that have elapsed since they became exposed. Producers turn to these deposits for large blocks. Stress is stored only in deep deposits beneath a flat bedrock floor and then only in rocks with high modulus of elasticity.

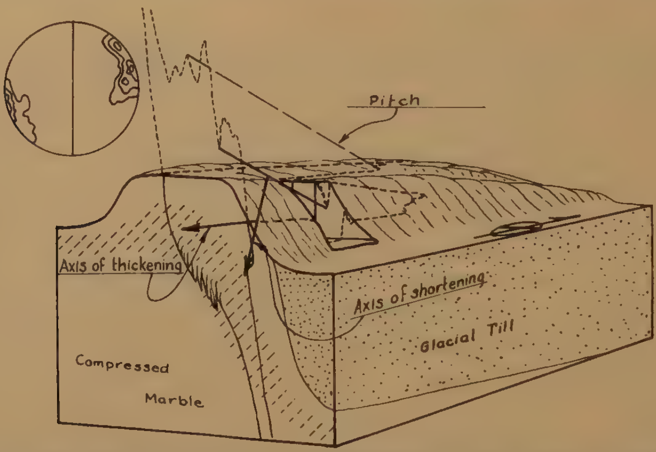

FIG. 1.—STRUCTURAL RELATIONS AT PITTSFORD VALLEY QUARRY, VERMONT. The boundary zone (cross lined) between highly compressed rock distant from a free surface and relieved rock adjacent to one is indicated on the east-west face of the block. Spontaneous expansion is along the axis of thickening. An orientation diagram for *c* axes of calcite crystals in the thickened section is inset at the upper left.

PROBLEMS OF THE CHEMICAL TYPE

The chemical problems fall into three categories: (1) solution phenomena, (2) decomposition phenomena, (3) utilization of marble waste.

Solution Phenomena

Limestone belts characteristically form valley regions but unjointed areas in them project as isolated hills and indicate that access of weathering solutions to all parts of the rock is essential for disintegration. Also, many marble structures and monuments have deteriorated, partly because of age (for marble was worked in this country for 50 years before other common building stones came into general use) and partly because some varieties had wide openings, which rendered the stone more accessible to solutions. Although the 125-ft. cliff at Pittsford Valley has glacial markings preserved in all detail on exposures of the A, B, C and G_2 layers, the intervening D, E, F and G_1 layers have weathered back ½ to 2 in. Many marble monuments of the Revolutionary period preserve their sculpture in all perfection and far outnumber the monuments that have disintegrated (Fig. 2). Study shows that weather-resistant types have narrower intergranular spaces and more irregular grain borders than rocks of similar appearance that have failed to behave so well.

Shaded and low sections of a stone that are continuously wet and cool do not weather noticeably. Age effects appear first above this zone as a slight darkening of the sections that wet and dry with greatest rapidity, especially in the vicinity of carvings and corners. Advanced stages show a rough surface and the color changed to an old ivory tone. Marble can be selected to show this antique color in 15 years or fail to show any stages of aging after a century.

Aging is due to solution of grain borders and twin planes to form depressions that catch dust to give the stone a gray tone. Eventually the small grains fall out; the large ones are held by interlocking contact with others behind them. Dust shows through from behind and appears as a diffused cream tone. Enlargement of space and cementation of dust is due to fluids moving through the intergranular spaces and evaporating at the surface of the stone. Precipitation occurs back of the outer layer after the cream tone has developed and minimizes further loss of grains.

Solutions entering the rock may be either rain water with dissolved atmospheric gases, rain water with a complex group of salts gathered from accumulated efflorescences on the surface of the stone, or ground-water salts. Absorption tests on different varieties of marble treated repeatedly with rain water indicated negligible enlargement of intergranular space. Similar treatment with salt solutions, many of a type found in ground water, showed that all were detrimental (Table 1). Greatest weathering of structures occurs in the zone where solutions are evaporated at the surface. Consequently weathering is attributed largely to ground-water moisture, or to rain water carrying accumulated efflorescences back into the stone and dissolving material along grain borders, which later, upon evaporation, forms an incoherent deposit at the surface.

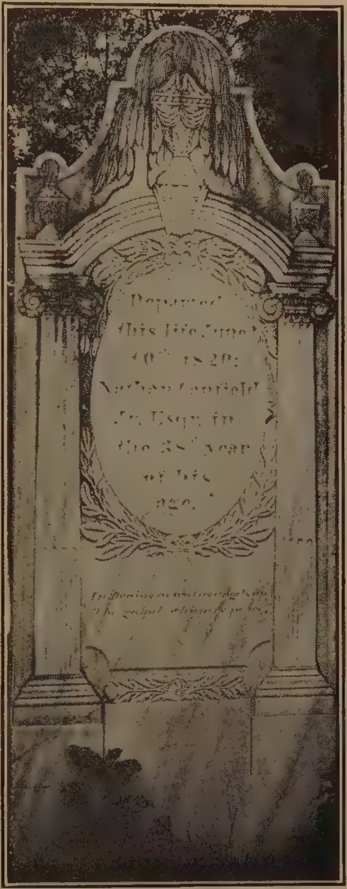

Fig. 2.—Old marble monument at Arlington, Vermont.

This marble is in excellent preservation. Note detail of window, leaf design at top. Basal planes of calcite are parallel to face and grain irregularity is 1.86 (Table 3).

Weathering may be retarded by impotency of solutions or by low volume of solutions passing in and out of the rock. Impotency exists only where rain water is pure and efflorescences are removed by annual

TABLE 1.—*Effect of Different Salt Solutions upon Marble*

Specimen No.	Type of Solution	Effect[b]								Type of Marble
		A	B	C	D	E	F	G	H	
19	$CaSO_4$ saturated	0.0855	0.0935			4.13	9.36			Riverside Danby
21	$CaSO_4$ saturated	0.0849	0.0923			7.55	8.72			Riverside Danby
23	$CaSO_4$ saturated	0.1523	0.1660			1.85	8.98			Pittsford Valley average
22	$BaCl_2$ saturated	0.1462	0.1680			2.16	14.90			Pittsford Valley average
24	$BaCl_2$ saturated	0.1373	0.1642			5.13	19.57			Pittsford Valley average
17	$BaCl_2$ and $CaSO_4$[a]	0.1489	0.1685			3.77	13.17			Veined Rutland Italian
26	$BaCl_2$ and $CaSO_4$[a]	0.1655	0.2032	0.2510		−1.04	22.80	23.54		Coarse light Rutland Italian
32	$BaCl_2$ and $CaSO_4$[a]	0.1755	0.2140	0.2697		10.23	21.94	26.00		West blue marble
29	$BaCl_2$ and $CaSO_4$[a]	0.1470	0.1560			9.64	6.13			Pittsford Valley quarry No. 7
18	$BaCl_2$ and Na_2SO_4[a]	0.1598	0.1928			−0.12	20.65			Veined Rutland Italian
27	$BaCl_2$ and Na_2SO_4[a]	0.1710	0.2205	0.2780		−3.43	28.95	26.08		Coarse light Rutland Italian
33	$BaCl_2$ and Na_2SO_4[a]	0.1747	0.2255			12.36	29.08			West blue marble
30	$BaCl_2$ and Na_2SO_4[a]	0.1434	0.1729			6.45	20.55			Pittsford Valley quarry No. 7
16	$BaCl_2$ and $(NH_4)_2SO_4$[a]	0.1395	0.1759			1.76	26.10			Veined Rutland Italian
25	$BaCl_2$ and $(NH_4)_2SO_4$[a]	0.1750	0.2190	0.2532		3.60	25.15	15.60		Coarse light Rutland Italian
31	$BaCl_2$ and $(NH_4)_2SO_4$[a]	0.1602	0.2180			5.86	36.05			West blue marble
28	$BaCl_2$ and $(NH_4)_2SO_4$[a]	0.1370	0.1579			7.23	15.25			Pittsford Valley quarry No. 7
1	$BaCl_2$ and $MgSO_4$[a]	0.2375	0.2480	0.4200	0.5000		4.42	69.40	46.50	Light Rutland Italian
2	$BaCl_2$ and $MgSO_4$[a]	0.2690	0.2644	0.4265	0.4760		−1.71	61.30	30.50	Light Rutland Italian
5	$BaCl_2$ and $MgSO_4$[a]	0.1518	0.1449	0.2721	0.3130		−4.54	87.90	32.10	Veined Rutland Italian
6	$BaCl_2$ and $MgSO_4$[a]	0.1391	0.1492	0.2520	0.3130		7.25	68.80	59.40	Veined Rutland Italian
15	$BaCl_2$ and $MgSO_4$[a]	0.1682	0.1551	0.3022	0.3552		−7.79	94.90	36.00	West blue marble
14	$BaCl_2$ and $MgSO_4$[a]	0.1695	0.1790	0.3122	0.3608		5.60	74.50	36.50	West blue marble
11	$BaCl_2$ and $MgSO_4$[a]	0.1359	0.1315	0.1778	0.3225		−3.24	35.20	313.00	Pittsford Valley average
12	$BaCl_2$ and $MgSO_4$[a]	0.1345	0.1448	0.2030	0.2425		7.66	40.20	67.80	Pittsford Valley average
8	$BaCl_2$ and $MgSO_4$[a]	0.1395	0.1375	0.2400	0.2660		−1.50	74.50	25.40	Riverside Danby
9	$BaCl_2$ and $MgSO_4$[a]	0.1550	0.1545	0.2475	0.2775		−0.32	60.10	32.30	Riverside Danby

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[a] Saturated $BaCl_2$ solution is allowed to penetrate the stone for ¼ in. The test piece is then transferred to a bath containing a saturated solution of the particular sulphate indicated. The sulphate is allowed to drive the $BaCl_2$ solution ¼ in. farther into the stone. The test pieces are moved back and forth from $BaCl_2$ to sulphate bath until they are saturated, thus mixing the solutions inside the stone. The test pieces are dried and then saturated with distilled water after treatment to remove unused solution.

[b] A, absorption of untreated test piece.
B, absorption of rock saturated once by solutions as described in footnote *a*.
C, absorption of rock saturated twice by solutions as described in footnote *a*.
D, absorption of rock saturated three times by solutions as described in footnote *a*.
E, percentage increase in absorption per treatment with distilled water only.
F, percentage increase in absorption due to first treatment with salt solutions.
G, percentage increase in absorption due to second treatment with salt solutions.
H, percentage increase in absorption due to third treatment with salt solutions.

TABLE 2.—*Relation of Amount of Solution to Width of Openings*

Specimen No.	A[a]	B	C	D	E	F	G	H	I	J	K	L	M	N	Type of Stone
18	0.1598	0.00436	0.1928	1	0.0330	0.000901	0.0160	0.000437	0.000247	0.001148	150.8	1851	0.00000235	7.6	Veined Rutland Italian
A	0.1068	0.00291	0.2878	3	0.1810	0.004941	0.0378	0.001031	0.000583	0.005524	112.1	1190	0.00000245	7.9	Colorado Yule golden vein
B	0.1350	0.00369	0.3100	3	0.1750	0.004780	0.0535	0.001460	0.000826	0.005606	114.9	1231	0.00000299	9.6	Colorado Yule statuary
2	0.2690	0.00735	0.4760	3	0.2070	0.005650	0.1490	0.004070	0.002300	0.007950	174.1	2300	0.00000319	10.3	Fine light Rutland Italian
26	0.1655	0.00451	0.2510	2	0.0855	0.002335	0.0340	0.000929	0.000525	0.002860	94.5	919	0.00000491	15.8	Coarse Rutland Italian
C	0.1320	0.00360	0.1915	3	0.0595	0.001620	0.0305	0.000833	0.000471	0.002091	16.6	67.6	0.00005320	171.5	Silver gray Georgia
D	0.1680	0.00459	0.1670	3	−0.0010	−0.000030	0.0241	0.000658	0.000372	0.000342	16.8	68.7	0.00006690	216.0	Silver gray Georgia
E	6.6900	0.18260	6.0500	3	−0.6400	−0.017500	0.4350	0.011880	0.006710	−0.010790	Openings large for hydraulic flow				Indiana limestone

[a] A, initial absorption of the stone, per cent by weight.

B, initial space, c.c. per c.c. of stone.

C, absorption of stone, per cent by weight after treatment. Treatment consisted of alternate applications of $BaCl_2$ and Na_2SO_4 solutions until stone was saturated.

D, number of treatments. Stone was dried out and washed in distilled water after each treatment to remove unused solutions.

E, resultant increase in absorption, per cent by weight.

F, resultant increase in pore space, c.c. per c.c. stone.

G, actual gain in weight of test cubes under treatment due to precipitation of $BaSO_4$ in openings.

H, actual gain in weight per c.c. stone.

I, amount $BaSO_4$ deposited in place of $CaCO_3$ to account for weight and pore-space increase simultaneously. Amount equal to values in column H divided by 1.77 (difference between specific gravity of barite and calcite).

J, total calcite displaced per c.c. rock as result of treatment. Equal to sum columns F and I. This space is effective space produced for mineralization by saturated solutions.

K, linear contact between grains for each square centimeter of crystalline limestone.

L, area of contact between grains in one cubic centimeter of crystalline limestone.

M, width of space between grains. This value equals column B divided by column L and is given in centimeters.

N, width of space between grains given in terms of diameter of water molecules.

cleaning. Other factors are influenced by internal features of the marble. For the second of these causes, stones weather only slightly or not at all for the first 8 in. above ground; thus ledgers and low markers retain their carving almost indefinitely.

Salt solutions do not affect equally even marbles that are similar in appearance (Table 2, column C). Stones with openings less than 2.5 millionths of a centimeter wide yield to solution slowly and those with openings about 3.5 millionths of a centimeter wide dissolve most rapidly. Solution diminishes where openings exceed 6 millionths of a centimeter but frost begins to cause disintegration. The solutions become less effective as they widen the openings and the rate of weathering decreases.

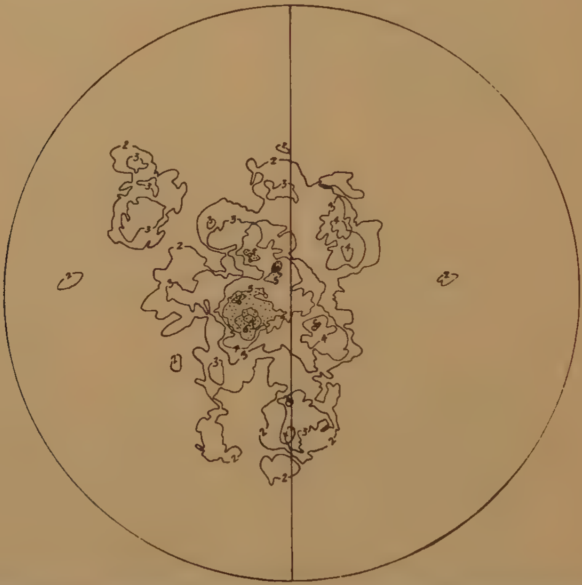

Fig. 3.—Orientation diagram for *c* axes of calcites on headstone in Fig. 2. Contours represent percentage of poles of *c* axes in 1 per cent of the area of this polar projection diagram. Areas with more than 5 per cent of the poles are stippled. The pole of an axis perpendicular to the face of the headstone emerges in the center of the diagram.

Many marbles with the same widths of openings vary widely in durability, so that width of openings is not the only factor. Experimentally calcite has been found to be much more soluble on the edge of the prism than on the basal face. Some marble blocks have crystal axes of calcite grains oriented parallel to one another and therefore behave as a crystal; such blocks have two weather-resistant faces and four weather-weak ones. Other blocks have crystal axes of calcite grains arranged at random; one grain may have its soluble face exposed and its neighbor may present a resistant basal face to the weather. Solution removes only the weak grain, and the first resistant face halts further recession. All surfaces of such marble blocks weather uniformly but none resist weather as well as the weather-resistant face of varieties with parallel orientation. Parts of deposits with oriented marble are limited to the vicinity of shear folds. Intervening slightly deformed sections have rock with a lower degree of orientation. The orientation for the ancient headstone in Fig. 2 is shown in Fig. 3.

Monuments supplied from one highly folded section of the West Rutland deposit developed knots or augen of unweathered marble even when the matrix around them weathered badly. Width of openings and chemical composition were the same in matrix and augen. However, untwinned grains making up half of the matrix had their crystallographic basal planes almost perpendicular to the surface. The same type of grains in the augen were more numerous and had their basal planes inclined at a very pronounced angle to one another and to the exposed surface, thus presenting many weather-resistant basal surfaces. Furthermore, irregularity of grain borders was greater and the texture coarser in the augen than in the matrix. These fabric features affected significantly the weather resistance in this particular rock.

TABLE 3.—*Coefficients of Irregularity for Some Typical Marbles*

Specimen No.	Grains per Sq. Cm.	Contact, Cm. per Sq. Cm.	Coefficient	Type of Marble
1	5,980	150.8	1.95	Veined Rutland Italian
8	5,980	145.5	1.88	Augen in Rutland Italian
9	6,800	142.5	1.73	Matrix of augen in Rutland Italian
4	7,600	174.1	2.00	Fine, light Rutland Italian
10	4,280	105.8	1.62	Dark Rutland Italian
2	3,140	112.1	2.00	Colorado Yule golden vein
3	3,100	114.9	2.06	Colorado Yule statuary
11	4,100	122.3	1.91	Colorado Yule statuary
12	2,180	91.3	1.95	East side Yule statuary
13	1,455	69.1	1.81	Danby Metawee marble
14	2,280	88.9	1.86	Pittsford Valley *A* layer at glacial striation locality
15	2,540	97.3	1.97	Pittsford Valley No. 7 marble
16	2,560	94.2	1.86	Old monument, Arlington, Vt.
17	3,180	109.0	1.77	Scaling monument, Arlington, Vt.
7	76	16.5	1.93	Silver gray Georgia marble
8	80	16.8	1.85	Silver gray Georgia marble

Grain contacts so irregular that grain holds grain as the clasps hold a gem in a ring are desirable in marble that is to be exposed to rigorous attack of frost and ground water. It has been found that the length of contact between grains on any surface divided by the square root of the number of grains exposed on that surface is approximately 1.8 (Fig. 4). This is called the coefficient of irregularity and may be 2.1 for marbles with very irregular grain borders and only 1.65 in smooth types. No old monument or glaciated ledge examined has had a coefficient below average and no badly disintegrated surface in unpolluted atmosphere has been above average. Determinations for some typical marbles are given in Table 3. Marbles from deposits having wide variation in degree of deformation in short distances, as at West Rutland, Vermont, have widest variation in irregularity coefficient.

Discolorations and Decomposition Phenomena

Unequal wetting of a stone causes the wetted part to appear dark. Excess magnesium chloride, used in setting, forms local areas of deliquescent salt and is a frequent cause of unequal wetting; another is local variation in pore widths in the stone itself. Traces of pyrite or other iron-bearing sulphides have proved troublesome and cause discolorations whose removal is one of the most tedious tasks conceivable. "Vaccination" with barium fluoride has been found to be a preventive of stain trouble in stone suspected of having sulphides.[1]

A thin air film separates the grains of calcite. The index of refraction of the extraordinary ray in calcite is 1.486 and light is reflected back into calcite from the grain border where the angle is 42°20′ or greater. Water fills the space in wetted stone and light is transmitted across the film until the angle is 63°30′ or higher. Few light rays are reflected back at wetted grain contacts; moreover, light penetrates deeper and is absorbed, so that the marble appears darker. This is annoying to many people but it may appear in any untreated stone.

Total amount of openings is proportional to width in rocks of the same grain size. Both are lower along green silicate veins and other mineralized zones than through white marble (pp. 511–512 of ref. 2). Conversely, the openings are wider around inscriptions and figures carved on the face than elsewhere except when the work is done with precautions described later. From openings wide by nature or by workmanship water evaporates more rapidly than from areas with narrow spaces, so that a stone will appear spotted as it dries unevenly after rain. This is particularly true of marble with exceedingly narrow openings. If a purchaser objects to this feature, the only remedy is to impregnate the stone for $\frac{1}{3}$ in. with a water-insoluble, colorless, lightfast, crystalline substance having a melting point above 110°C.

Green stains develop wherever water passes from copper-bearing materials, such as bronze tablets and copper roofs, to marble. Such stains have not been removed successfully but two preventive measures are possible for the most objectionable feature. Two types are recog-

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[1] References are at the end of the paper.

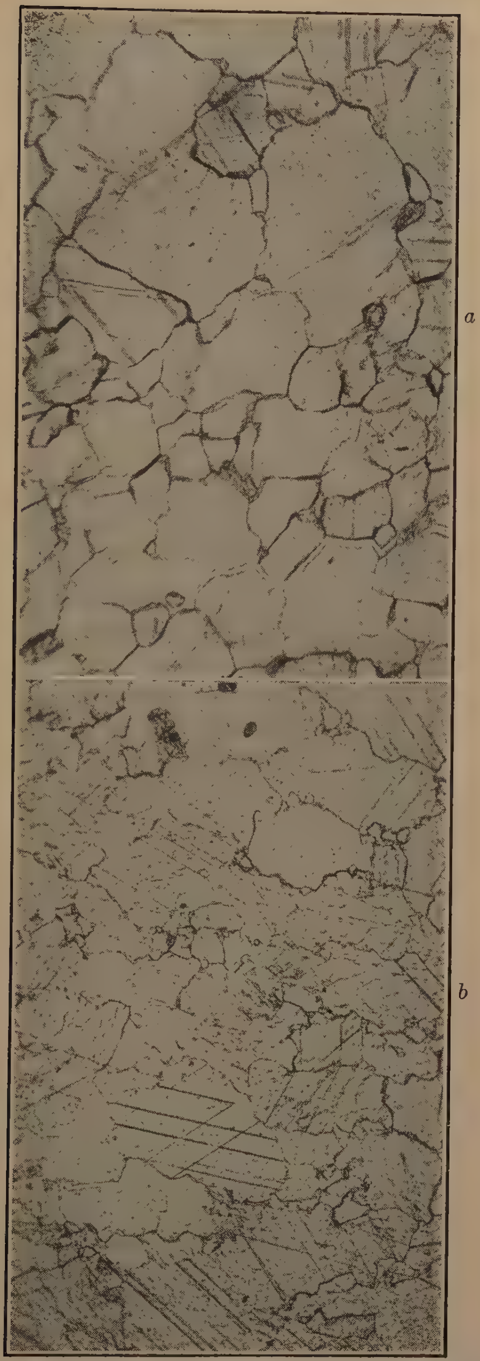

FIG. 4.—SMOOTH-GRAINED MARBLE CONTRASTED WITH IRREGULAR-GRAINED TYPE.
Dark lines are refringent bands marking grain limits. Note greater width and irregularity in smooth type (above) than in irregular type (below).

nized and they do not penetrate far from the surface or open joints. The green basic carbonate is first to appear and is attractive; later it changes to the red oxide on surfaces that wet and dry frequently, giving oxygen access to the earlier deposit. The stone becomes fissured near the red areas. The oxide does not form on continuously wetted surfaces, such as fountains. Also, any hydrocarbon impregnant that will exclude oxygen prevents the formation of the red copper oxide and forestalls disintegration.

Oxalic acid is a favorite polishing reagent and is used to facilitate hone finishing. It softens the surface and speeds up the operation. Tests of its solvent power on marble showed that it doubled the width of openings in many varieties for each application. Softening is due to solution around the surface grains, especially in capillaries and at points of applied pressure.

Utilization of Marble Waste

Lime and rock granules are two developed outlets for waste and rock wool has been studied experimentally. Pure calcite marble waste yields high-calcium lime for chemical industries and hydrated lime for building plaster. The rock must be relatively free from silicates; slightly impure waste is not high enough in magnesium to make good agricultural lime. Rock granules are used for coating nonfading wall paper and paper filler and for maintaining a neutral soil. Wall-paper granules must be uniformly white; marble with more than 10 per cent of dark green silicates is not acceptable. Siliceous bands in quarry waste are discarded. Granules from gray marble appear white. Silicated rock discarded at Danby, Vt., can be mixed with an equal amount of local slate to produce a mixture suitable for rock wool.

PROBLEMS OF A PHYSICAL TYPE

The physical problems arise largely from intended use for the stone. They include such requirements as high translucence, limited rigidity or flexibility, and low warping under moisture absorption. Problems also arise from transmission of fabrication shocks, which tend to weaken the union between crystal grains. Each problem requires geological interpretation of the physical effect of fabrication or of use upon the stone.

Characteristics of Translucent Marbles

Light-transmitting power is very different in various samples of marble but adjacent translucent slabs should appear to have equally intense illumination. Also, internal reflections must be retained, so that the surface will appear crystalline in direct light and yet he kept near a minimum in translucent marble.[3] Highest light transmission for calcite and minimum refraction are for rays normal to the *c* axis of the crystal. Pressure reorients calcite of many fine-grained marbles with the basal plane perpendicular to the stress. This causes a high degree of orientation to the vertical or *c* axes. The direction of a majority of vertical crystal axes is determined for a particular piece of oriented marble; the block is then sawed into slabs with this direction parallel to the surface. Test pieces sawed with care for the predetermined crystal structure give light-transmitting coefficients that lie in a narrow range in comparison to random slabs. Efficiency and beauty of Lumar are enhanced greatly by this attention to detail. Increasing intensity of illumination for less translucent varieties fails to bring out the crystalline appearance. Orientation of coarse Danby and Georgia marble to be used for Lumar is important but the same improvement in light transmission by application of methods like those described above is not possible.

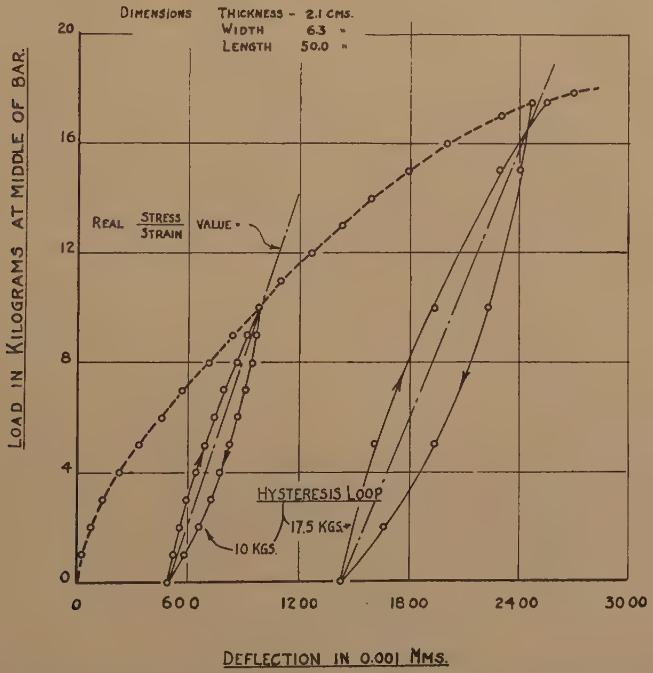

FIG. 5.—STRESS-STRAIN RELATIONS IN LOADED BAR OF MARBLE.
Axes of hysteresis loops represent elastic stress-strain relationship. Deflection of lower end of hysteresis loop is permanent distortion. It increases with stress and so indicates variable ease of opening and closing intergranular space.

Elasticity and Flexibility Problems

Mausoleum shutters, slabs and counters occasionally warp. In an extensive study of elasticity of marble under bending stress, the variation was found to be very great (Table 4). Elasticity is related to the amount of space between grains and irregularity in outline of constituent grains. These properties are dependent upon the geologic structure in the quarry, so that general elastic quality of the stock from different sections can be estimated before quarrying.

Dependence of flexibility upon width of openings is demonstrated easily. A supported bar is depressed by a load in the middle; unloading causes a partial return. The difference between the depression and the elastic return is the permanent distortion (Fig. 5). When the bar is inverted, the permanent distortion under load is twice the original amount. Spaces on the upper side of the bar were opened to twice the initial width by initial permanent distortion, whereas those below are closed proportionately; this allows a double elongation and compression when load is applied to the inverted bar.

TABLE 4.—*Relation of Pore Space to Flexibility*

Specimen No.	Pore Space	Young's Modulus, Kg. per Sq. Cm.	Deflection, Mm.		Type of Marble
			Total	Elastic	
1*a*	0.1606	4.225×10^5	0.485	0.455	Yule
1*b*	0.1606	4.190×10^5	0.485	0.455	Yule
2*a*	0.1515	3.775×10^5	0.570	0.515	Yule
2*b*	0.1515	3.625×10^5	0.625	0.530	Yule
3*a*	0.1562	4.010×10^5	0.525	0.485	Yule
3*b*	0.1562	3.840×10^5	0.505	0.505	Yule
4*a*	0.3910	0.711×10^5	8.91	2.69	Rutland
4*b*	0.3910	0.706×10^5	1.57	2.71	Rutland
5*a*	0.2190	1.938×10^5	8.83	1.08	Rutland
5*b*	0.2190	2.092×10^5	1.73	1.01	Rutland

Marbles having exceedingly low pore space—and high elasticity—are recommended for unsupported shutters and counters. Flexible stones are adaptable to a structure that may settle, causing uneven or concentrated stress on the stone.

Warping Problems

Warping is imminent wherever stone is moistened unevenly; for example, moisture condenses on walls of poorly ventilated mausoleums and one side of a slab becomes moist while the other remains dry. Water adsorbed on the crystals exerts pressure on the capillary walls to cause widening of openings on the wetted side and warping of the slab (Fig. 6). Warping is reduced by using very elastic marbles for this sort of construction.

Fabrication Problems

Marble is handled carefully at all times; nevertheless variable opening of intergranular space can be identified. The elastic Yule marble can be finished to size on carborundum rubbers and rubbing beds without affecting width of pore space whereas flexible Rutland marbles have pores widened least by finishing on a sand bed (Table 5). Elastic marble resists the shearing stress from the rotating carborundum bed but the narrow openings and high elasticity of the rock transmit percussion shocks of the rolling sand to weaken the bond between individual granules. Flexible marbles have the intergranular space opened up by shearing stresses of the rotating carborundum bed but percussion shocks of the rolling sand bed are absorbed in the openings between grains. Thus the character of the stone materially influences its reaction to finishing processes.

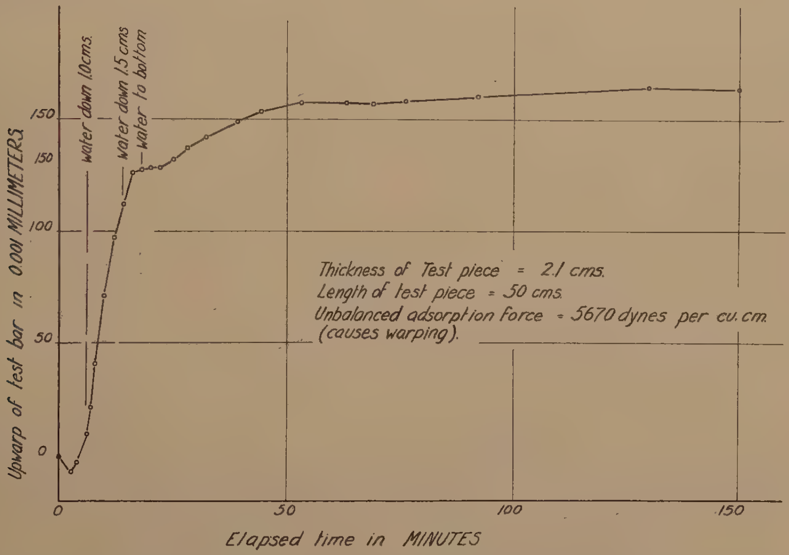

FIG. 6.—DEFLECTION OF TEST BAR TOWARD WET SIDE.

Slight initial contraction of wetted side, due to capillary force on walls of intergranular space, is followed by rapid expansion, which continues until entire bar is wet. Expansion is attributed to adsorption on walls of openings.

The depth of shock transmission and loosened grains is significant in many other finishing processes. Tooling, lettering, planing and drilling may increase the space between the grains almost twofold (Table 5). This is not serious for building and interior work but it is bad for monuments. Carborundum molding wheels produce only slight damaging effect. Pneumatic tools and the "chatter" of the planer open the granules of Yule marble but change Rutland only a small amount. The frequency and force of blow by carving tools are affected by the weight of the reciprocating piston and air pressure. A ⅝-in. pneumatic tool operated at 20 to 40 lb. pressure shatters the stone and widens pore space for an inch away from the work. Operated at pressures of 7 to 15 lb. and 45 to 55 lb., the same tool causes little damage.

TABLE 5.—*Effect of Fabrication Processes on Marble*

Operation	Machine Used	Change in Absorption,[a] Per Cent	
		Yule Marble	Rutland Marble
Rubbing to size	Carborundum bed	0	0
	Loose sand bed	20	−2
	Drum rubber	5	4
Cutting to shape	Molding wheel	15	0
	Planer	37.2	12
	Cut by pneumatic tool	56	11
Drilling dowell hole	Carborundum bit	52	41
	Pneumatic drill	36	19
	Twist drill	53	49
	Flat drill	0	19
Carving and lettering	Mallet and chisel	36	11
	Sand blast	5	7
	⅝-in. pneumatic: pressure 7 lb.	4	8
	Pressure 15 lb.	13	24
	Pressure 20 lb.	29	32
	Pressure 25 lb.	39	23
	Pressure 30 lb.	43	44
	Pressure 35 lb.	42	32
	Pressure 40 lb.	28	43
	Pressure 45 lb.	18	9

[a] Absorption change is checked against standard test pieces prepared on an alundum rubbing bed.

Pneumatic tools with a ½-in. cylinder have a higher frequency and do not damage the stone as much at any pressure as the ⅝-in. tool at the most favorable pressure. Letters cut with mallet and chisel by hand are very erratic. Sandblast carving does not injure the stone.

Strain at Reentrant Angles

Reentrant angles concentrate residual stress and often cause cracks similar to those that develop in metal castings; these are due to expansion rather than to contraction. The minimum radius of curvature on internal angles should be ¼ in. and preferably it should be more.

Sawing Problems

Drag saws are used for primary cutting. Loose grit in water suspension is rolled beneath a reciprocating blade and breaks percussion chips from the stone. High crushing strength of the grit particles is more important than hardness or angularity. At present steel shot is the fastest cutting material but it produces serious iron stains on white marble. Well rounded quartz sand is excellent; it cuts nearly twice as fast as angular glacial outwash and has twice the life of the latter. Alundum grain wears well and cuts rapidly but primary cost more than offsets the other economies.

Crushed garnet rock saws rapidly and has long life due to the high crushing strength of the garnet. Cutting speeds above those anticipated are attributed to the high specific gravity of the garnet, which causes it to settle rapidly into the saw cut and become available immediately for cutting. Specific gravity, as well as roundness, or freedom to roll, and high crushing strength, is an important attribute of abrasives for sawing.

Summary

The cause of the errants and development of selection methods to keep materials for their proper use and place is important to perpetuate the usefulness of quarries, plants, and personnel in the marble industry. A major poor selection reflects unfavorably on marble, as one poor product does in any manufacturing industry. Recognition and solution of these selection problems is a field in which the observant geologist can render valuable service.

Many individuals, from the quarryman to the salesman and architect, must be considered by any geologist working with industrial minerals; he must satisfy not one individual but a committee; he must evolve not one solution for a problem but as many solutions as the problem possesses. The best solution from a scientific viewpoint may not be the one acceptable to the industry. If he recommends that a certain type of stone be withdrawn from one outlet the geologist must be prepared to open another for it. Neither methods nor objectives are static; as methods are perfected and the product improves, the objective of a better method and a better product looms ahead.

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2. G. W. Bain: Mechanics of Metasomatism. *Econ. Geol.* (1936) **31,** 505–526.
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Large-diameter Core Drill for Geologic Exploration

By Berlen C. Moneymaker,* Member, and Portland P. Fox,* Junior Member A.I.M.E.

(Knoxville Meeting, October, 1938)

The development, within recent years, of core drills capable of drilling holes up to 72 in., or even more, in diameter, has made possible an entirely new and valuable method of geologic exploration. Although little used until recently as an exploratory tool except in the United States, by the Tennessee Valley Authority and the Corps of Engineers of the U. S. Army, for the exploration of damsites, the large-diameter core drill may be used to good advantage in other types of geologic exploration. Its principal utility is that of supplementing, rather than replacing, other means of exploration.

Although core is frequently recovered intact, the greatest advantage of large-diameter drilling is that the holes produced are large enough to be entered by the geologist and engineer, and thus afford an excellent means of examining undisturbed rock. The walls of the holes are smoothly cut, and in some rocks nearly or quite polished, so that the most minute details of structure and stratigraphy are clearly disclosed. Such features as faults, joints, bedding planes, weathered "seams," and beds or layers of soft materials, which are not always amenable to disclosure by cores recovered from small-diameter holes, are conspicuously displayed in the walls of large holes.

Frequent reference to the drilling of large-diameter holes is made in engineering literature, but comparatively little emphasis has been placed on their value in geologic investigation. It is, therefore, intended that the present paper acquaint the geologist, as well as the engineer, with the large-diameter core drill and the technique involved in its use, and also with its advantages, disadvantages and limitations as an implement of geologic exploration.

THE EQUIPMENT

The equipment generally employed in the drilling of large-diameter holes consists of a trunnion-type drill head mounted on a sliding base, which allows it to slide clear of the hole and thus permit the introduction

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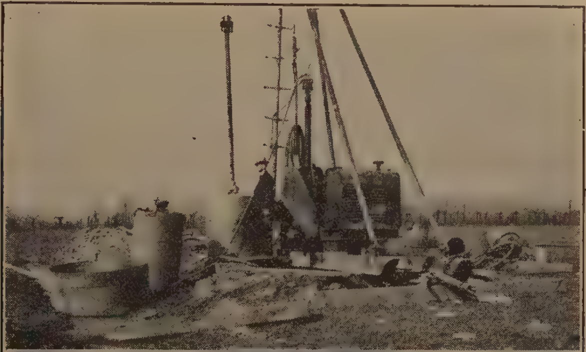
* Geologist and Assistant Geologist, respectively, of the Geologic Division of the Tennessee Valley Authority, Knoxville, Tennessee.

and removal of the tools; a countershaft fitted with a winch head for hoisting; and an electric or gasoline motor, all of which are mounted on a structural-steel frame equipped with skids (Fig. 1). Most of the rigs used in the Tennessee Valley area also have an auxiliary air hoist. The bits used are steel cylinders of the required diameter, and from 30 to 60 in. high, closed at the top for attachment to the drill rods and notched at the base (Fig. 1). Bits with ½ to ¾-in. walls are generally used, as it is difficult to keep the cutting medium under thinner bits, and thicker ones tend to reduce the cutting speed. Ordinarily steel shot is employed as the cutting medium but crushed steel is used in cutting rock that is so soft that the shot, instead of crushing, becomes embedded in the walls of the hole. Bits set with removable steel or hard alloy teeth are sometimes used in shales and other soft rocks.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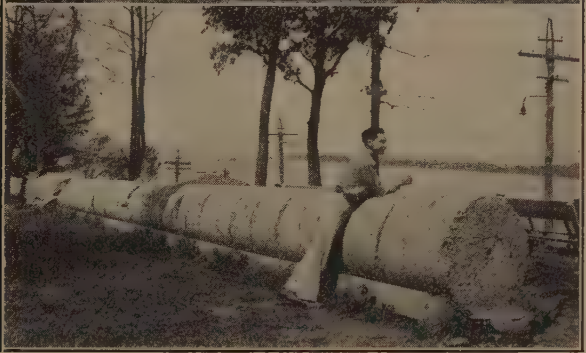
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Fig. 1.—Large-diameter core drill and bits (Ingersoll-Rand WS3 calyx drill).
Fig. 2.—Core recovered from 36-inch hole drilled in limestone at Wheeler dam on the Tennessee River in Alabama.

Drilling Procedure

As in any other kind of core drilling, the technique employed in the drilling of large-diameter holes varies considerably, depending largely upon the character of the ground to be drilled. In spite of the great variety of geologic conditions encountered in the Tennessee Valley area, where a considerable amount of large-diameter core drilling has been done, the drilling procedure has varied little. In the main, three operations are involved in the drilling of large holes, and although they are the same as those involved in small-diameter (diamond or shot) drilling, the procedures by which they are accomplished are quite different. The three operations are: (1) the removal of the overburden, (2) the drilling of the hole, and (3) the extraction of the core.

Removal of the Overburden.—The method employed in getting through the overburden depends, necessarily, upon the character of the material to be penetrated. In dry, residual or alluvial materials, sufficiently stable to stand for a while, a vertical shaft may be sunk to bedrock and a supporting timber crib built up within. In materials that tend to slough or flow, and that are under water, steel casing of somewhat larger diameter than that of the proposed hole is commonly used.* The casing is usually driven or rotated to rock and the overburden is removed from it by means of a clamshell or "orange peel," or by hand mucking, but it may be lowered by removal of the overburden from beneath it. After the casing is seated on bedrock, and the overburden removed, the hole may be carried to the required depth by drilling.

Drilling.—Drilling is accomplished by the rotation of a bit, supplied with a cutting medium (steel shot, crushed steel, or steel or hard alloy teeth), at a speed of about 50 r.p.m. The speed of drilling depends upon the hardness, texture and structure of the rock. Fissile shales, quartz-free mica schists and other soft rocks may be cut at the rate of several feet per hour, but the difficulties involved in the extraction of the core may result in slow drilling progress. Thick-bedded, flat-lying limestones free from chert are cut from a few inches to 2 ft. or more per hour; thin-bedded, steeply dipping or cherty limestones are cut much more slowly. Some sandstones are easily cut at a rate of 3 ft. or more per hour, although other sandstones, as well as most quartzites, gneisses and granites are cut only a few inches per hour. In sedimentary rocks, from 6 to 9 ft. in a shift of 8 hr. is considered good drilling progress.

Extraction of Core.—Except in flat-lying sedimentary rocks, it is necessary to break the core loose from the bottom of the hole, by placing light charges of explosive at one or more points in the groove cut around the core. If the core has sufficient solidity and strength, it is hoisted from the hole by means of a steel hoisting pin and wedge placed in a jackhammer hole drilled in its center. A large-diameter core recovered in this manner is shown in Fig. 2. Fissile or friable rocks, such as shales, shaly limestones and schists, and highly fractured rocks, which cannot be extracted from the hole as solid core, are ordinarily removed by mucking. At Fort Peck, the soft Bearpaw shale was broken up and lifted from the hole by means of a large auger equipped with scarifying teeth.[1,2] In the drilling of large-diameter holes, large quantities of water are not infrequently encountered, but except in exceedingly open and permeable rock it is usually amenable to control. Water in amounts not exceeding 100 gal. per min. may be successfully handled by pumping, but for greater amounts other methods of control must be employed. Often it is necessary to grout the rock in advance of drilling. This may be accomplished by means of a few grout holes drilled within the circumference of the proposed hole, or by a sufficiently greater number of properly located grout holes drilled just outside of it. Holes drilled in a stream or in unusually wet ground must be protected by a watertight cofferdam of sufficient stability and strength. This may be done by driving or rotating a steel cylinder of suitable diameter to bedrock, and effecting a seal by pouring 2 or 3 ft. of concrete on bedrock in the bottom of it after the removal of the overburden.

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* For 30, 36 and 40-in. holes, 54-in. casing with ¼ to ½-in. walls, in 6-ft. lengths is usually used.

LARGE-DIAMETER CORE DRILLING AS A METHOD OF EXPLORATION

Large-diameter core drilling is now an accepted method of geologic exploration, particularly of damsites. The method is equally applicable to the investigation of foundations for bridge piers, skyscrapers and other heavy structures. Moreover, certain mineral deposits, especially those containing soft materials that cannot be successfully recovered in small-diameter cores, may be advantageously explored by large-diameter core drilling.

A thorough geologic study of the foundation of any proposed engineering structure should disclose every discoverable detail of geology that may possibly have a bearing upon the success of the project under consideration. Often the major features may be determined by a preliminary geologic examination of the area, but frequently not even the major features are evident without exploratory work. The geologist is at an acute disadvantage in areas of glacial drift, extensive flood plains, and deep weathering. Even where outcrops are numerous, or where excellent selections are exposed near by, assumptions and predictions may prove to be quite erroneous. Although the geologist may know the age, thickness, extent, lithology and faunal character of every bed or rock mass involved in a foundation, he cannot always predict with absolute certainty the conditions to be encountered at a given point below the surface. Consequently, exploration based upon the recommendations of a geologist, and calculated to reveal necessary additional information, must be undertaken. Until recently, such exploration has consisted mainly of small-diameter (diamond or shot) core drilling, wash-boring, trenching, test-pitting, tunneling, and shaft-sinking. Of these methods, test-pitting,

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[1] References are at the end of the paper.

wash-boring and trenching reveal, at best, the thickness of the overburden and the configuration of the rock surface. Tunneling and shaft-sinking are time-consuming as well as expensive, and are not entirely satisfactory because of the shattering of the rock through which they are excavated in consequence of blasting. Small-diameter core drilling by means of diamond or shot drills is an excellent means of exploration, although it has certain limitations. Many materials are not recoverable, or are poorly recoverable, as cores, and frequently it happens that serious defects are recorded merely as core losses.

All rocks may have certain features that are objectionable in foundations and abutments, especially of dams, which may not be precisely determined by any of the commonly employed exploration methods. Joints and faults are secondary structural features that may occur in any rock, regardless of class, origin, age or lithologic character. These structures, as well as such primary structures as bedding planes and flow contacts, have, by facilitating the ingress of water, resulted in weathered seams and decomposed layers. Rocks of each class are characterized by certain features that may render foundations, especially of dams, defective. In the sedimentary rocks, beds of soft shale, bentonite and poorly cemented sandstone commonly occur. Gypsum and the carbonate rocks, such as limestones, dolomites and calcareous sandstones, are soluble and are generally characterized by open or filled solution cavities of various dimensions. The metamorphic rocks include soft or weak materials, such as layers or lenses of mica schist, chlorite schist, talc schist and cavernous marble, as well as various kinds of weathered zones or seams. Igneous rocks of plutonic origin are likely to be free from soft seams and zones, except those resulting from deformation or weathering, or both. Extrusive (volcanic) rocks are to be regarded with suspicion, however, as lava flows may be interlayered with weak or porous layers of fine to coarse fragmental materials. Moreover, the lava flows themselves may contain "tunnels" formed by the continued flow of the interior portions after the freezing of the outer surfaces. None of these features may always be accurately determined by ordinary small-diameter core drilling, as they are represented, to a very large extent, by core losses.

Scientifically conducted and intelligently interpreted small-diameter core drilling may show that a given foundation is entirely free from serious defects. In a great majority of cases, however, defects that may be serious are obscured in core losses, and it is highly desirable that a few large-diameter holes be put down at well selected points. Defects in a dam foundation or abutment overlooked during exploration but discovered during excavation and construction may necessitate the redesigning or relocation of the entire project. The discovery of a fault in the foundation of the dam on the Ocoee River, at Parksville, Tenn., caused a radical change in design after construction was well under way.[3,4] Such defects are easily discovered and studied when disclosed in the smoothly cut walls of large holes.

It is essential, also, for the proper designing of the projected structure, that the exploration disclose the details of the geologic structure and stratigraphy. In many instances, the required information cannot be satisfactorily obtained from small-diameter borings, and frequently it happens that such details as are obtained from different holes are difficult to correlate. Large-diameter holes are of great value in the working out of the necessary structural and stratigraphic details.

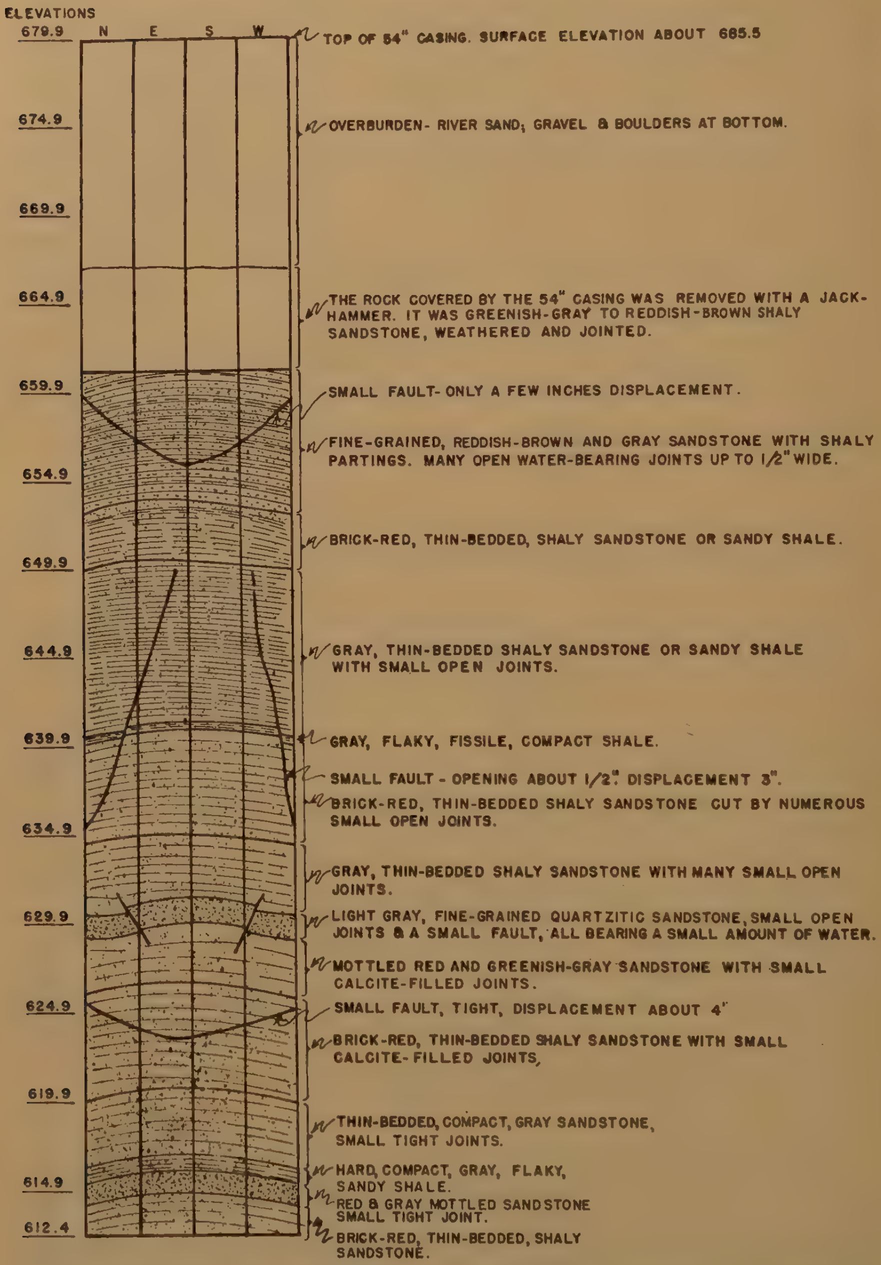
Large-diameter holes may be used also to excellent advantage in connection with grouting operations at damsites and elsewhere. They afford an excellent means of obtaining an exact knowledge of the nature of the openings to be filled, upon which the success of grouting very largely depends. After grouting has been undertaken, large holes may be used as a means of checking its effectiveness.

Although in some instances the mere inspection of a large-diameter hole may suffice, it is sometimes desirable or even necessary to prepare a log, not of the core, but of the hole itself. This is particularly true if the hole is to be used in the working out of the geologic structure. The geologist charged with the preparation of the log is lowered into the hole, usually on a boatswain's chair controlled by means of the auxiliary air hoist. As he descends, he reads the depth of cavities and significant stratigraphic or structural features from a steel tape or chain, suspended from the collar of the hole, and sketches the conditions on a specially prepared waterproof log sheet. If the structure is simple and the defects, if any, are conformable with respect to it, a single section normal to the strike may be sufficient, but if faults and irregular cavities occur, a sketch showing all four quadrants is desirable (Fig. 3). The precise determination of the strike and dip of the smoothly cut strata and structures in the hole by means of the Brunton pocket transit is somewhat difficult, but the task may be facilitated by the use of a narrow board about 30 in. long. In holes that penetrate the water table, as most holes do, there is usually enough water raining down the hole to necessitate the use of rubber boots, raincoat and hat.

EXPERIENCES AT DIFFERENT SITES

No two damsites are exactly alike or present precisely the same problems. A given kind of rock characterized by a given type of geologic structure, however, may be expected to present the same advantages and disadvantages wherever found. The value of the large-diameter core drill in exploring damsites in different kinds of rock may well be illustrated by reference to the problems actually encountered at a few sites.

At Wheeler Dam, on the Tennessee River about 15 miles upstream from Muscle Shoals, the foundation and abutments are, for the most part,


ELEVATIONS
679.9
674.9
669.9
664.9
659.9
654.9
649.9
644.9
639.9
634.9
629.9
624.9
619.9
614.9
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N
E
S
W
TOP OF 54" CASING. SURFACE ELEVATION ABOUT 685.5
OVERBURDEN- RIVER SAND; GRAVEL & BOULDERS AT BOTTOM.
THE ROCK COVERED BY THE 54" CASING WAS REMOVED WITH A JACK-HAMMER. IT WAS GREENISH-GRAY TO REDDISH-BROWN SHALY SANDSTONE, WEATHERED AND JOINTED.
SMALL FAULT- ONLY A FEW INCHES DISPLACEMENT.
FINE-GRAINED, REDDISH-BROWN AND GRAY SANDSTONE WITH SHALY PARTINGS. MANY OPEN WATER-BEARING JOINTS UP TO 1/2" WIDE.
BRICK-RED, THIN-BEDDED, SHALY SANDSTONE OR SANDY SHALE.
GRAY, THIN-BEDDED SHALY SANDSTONE OR SANDY SHALE WITH SMALL OPEN JOINTS.
GRAY, FLAKY, FISSILE, COMPACT SHALE.
SMALL FAULT - OPENING ABOUT 1/2". DISPLACEMENT 3".
BRICK-RED, THIN-BEDDED SHALY SANDSTONE CUT BY NUMEROUS SMALL OPEN JOINTS.
GRAY, THIN-BEDDED SHALY SANDSTONE WITH MANY SMALL OPEN JOINTS.
LIGHT GRAY, FINE-GRAINED QUARTZITIC SANDSTONE, SMALL OPEN JOINTS & A SMALL FAULT, ALL BEARING A SMALL AMOUNT OF WATER.
MOTTLED RED AND GREENISH-GRAY SANDSTONE WITH SMALL CALCITE-FILLED JOINTS.
SMALL FAULT, TIGHT, DISPLACEMENT ABOUT 4"
BRICK-RED, THIN-BEDDED SHALY SANDSTONE WITH SMALL CALCITE-FILLED JOINTS,
THIN-BEDDED, COMPACT, GRAY SANDSTONE, SMALL TIGHT JOINTS.
HARD, COMPACT, GRAY, FLAKY, SANDY SHALE.
RED & GRAY MOTTLED SANDSTONE SMALL TIGHT JOINT.
BRICK-RED, THIN-BEDDED, SHALY SANDSTONE.

FIG. 3.—SAMPLE LOG OF 36-INCH DRILL HOLE. (*P. P. Fox and L. F. Grant.*)

in silico-argillaceous limestones of the Fort Payne formation, the powerhouse foundation being in limestone of the New Providence formation. Except for a few broad, gentle flexures, the strata involved at the damsite are essentially horizontal. The rocks are intersected by numerous joints, which have afforded avenues for the circulation of ground water, thus promoting solution below the water table. The investigation of solution cavities below the water table by means of large-diameter core holes constituted the final phase of the foundation exploration program. After the completion of rock excavation, 36-in. holes were drilled into all vertical joints enlarged by solution. Each hole was drilled to the depth at which the joint being investigated ceased to be open, the average depth being in the neighborhood of 25 ft. below the bottom of the rock excavation. The large-diameter holes permitted the actual visual examination of defects in the rock underlying the dam and afforded also a means of treating them.

At the Guntersville Dam, on the Tennessee River near Guntersville, Ala., the foundation and abutments are in relatively pure and nearly horizontal limestone of the Bangor formation (unrestricted). An interstratified layer of impervious shale averaging 3 ft. in thickness occurs at the damsite under from 2 to 30 ft. of limestone. The shale serves as an effective barrier to the downward movement of water and has protected the underlying limestone beds from solution. Consequently, the underlying beds are nearly free from cavities, although the overlying beds are somewhat cavernous. The cavities, which are filled, partially filled or open, are for the most part horizontal openings along bedding planes, fed and interconnected by enlarged vertical joint "feeders." Many of the horizontal cavities are quite extensive and traceable over 200 or 300 ft. (Fig. 4). During the preparation of the foundation, several 36-in. holes were put down, affording an excellent means of studying the character and distribution of the cavities. Holes drilled along the vertical cavities were of particular value.

At Chickamauga Dam, on the Tennessee River just upstream from Chattanooga, Tenn., the foundation and abutments are in limestones of the Chazy, Black River and Trenton groups, long included under the old formation name of Chickamauga limestone. Numerous beds of bentonite and shale occur interstratified with the limestones. The rocks underlying the two earth dams are intricately folded and faulted and are intersected by numerous joints of various trends and inclinations, but the rocks under the spillway, powerhouse and lock chamber are, on the whole, less complex structurally, being inclined upstream at angles of from 10° to 30°. The limestones vary widely in character, purity and susceptibility to solution. A bentonite bed occurring near the base of the Cannon limestone has effectively shielded the underlying beds from solution so that they are free from cavities, except where the ingress of water is facilitated by structural conditions. The limestones overlying the bentonite bed are characteristically cavernous, the cavities being irregularly developed along joints and faults and to some extent along bedding planes.

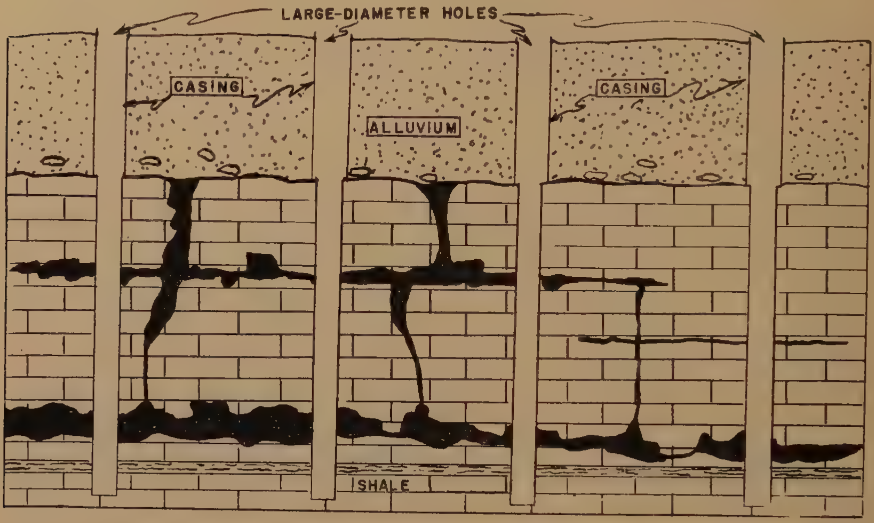

Fig. 4.—Large-diameter drill holes afford excellent means of exploring cavernous limestone.

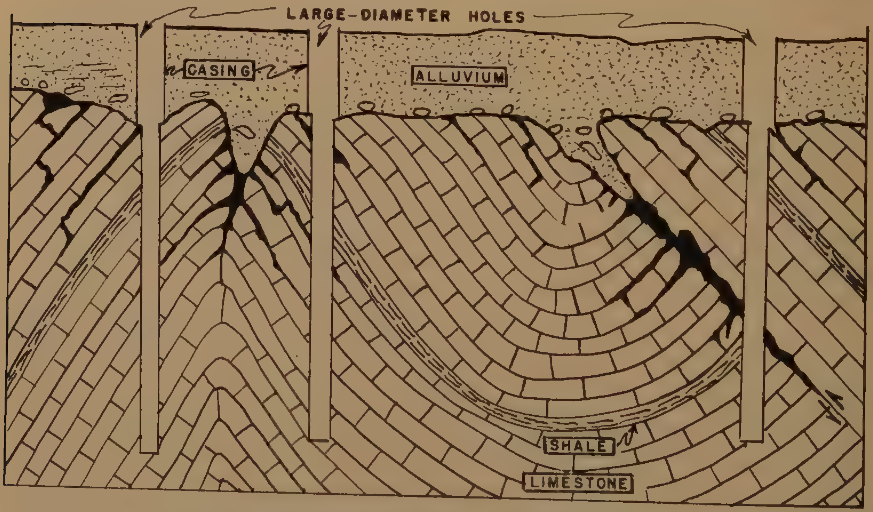

Fig. 5.—Large-diameter drill holes reveal geologic structure of damsite more clearly than small-diameter holes.

In the exploration of the Chickamauga site, several thousand feet of small-diameter core drilling was done. From this drilling, the geologic structure of the site was tentatively worked out and certain concepts relating to the character and distribution of the cavities were obtained. The shale and bentonite beds were rarely recovered in the cores, however, and a useful horizon marker was difficult to discover. Large-diameter drill holes enabled the geologists to discover the various soft layers that had been poorly recovered, or not at all recovered, in the small-diameter cores (Fig. 5). The different layers exposed in the smoothly cut walls of the large holes, precisely measured, afforded excellent horizon markers. By a re-examination of the small cores in the light of what had been determined from large holes, noting particularly the amount and position of core losses, the geologists were enabled to arrive at a more correct interpretation of the geologic structure, and intelligently to recommend necessary additional small and large-diameter holes as well.

As at the Wheeler and Guntersville sites, large-diameter holes were of considerable advantage at Chickamauga in the study of the cavernous condition of the limestones. Some of the features recorded as "clay seams" and "filled cavities" in the small-diameter core logs were shown by large holes to be the clay matrix separating large, jumbled limestone blocks in the overburden above the real top of rock. The large holes afforded a means of studying the openings to be grouted and a means of inspecting the effectiveness of the grouting as well.

At the Watts Bar damsite, on the Tennessee River near Spring City, Tenn., the foundation and abutments are in the Rome formation, which consists, locally, mainly of shale and sandstone. The rocks are all deformed by sharp folds and minor faults, and the shales are generally sharply contorted. The preliminary exploration at this site consisted mainly of small-diameter core drilling, although a few large-diameter holes were put down and a test trench was dug. The small-diameter holes afforded but little information of value, as the core loss averaged over 50 per cent, and at some places exceeded 95 per cent. As the geologic structure, which must be taken into account in designing the dam, could not be determined even approximately from the small holes, it was necessary to drill some large-diameter holes (Fig. 6). In the smoothly cut walls of the 36-in. holes, even the softest and most fissile shale and the minute faults and folds were clearly exposed. A few large holes drilled at selected points were sufficient to enable the geologist in charge to work out the main features of the geologic structure.

At Norris Dam, the foundation and both abutments are in the massively bedded cherty limestone and dolomite of the Copper Ridge (lower Knox dolomite) formation. The beds are gently inclined downstream (southeastward), the average dip being about 4°. Although much of the rock was extensively jointed, no faults were involved in the damsite. The exploratory drilling revealed the presence of numerous small cavities and seams in the foundation.

An extensive program of foundation treatment was undertaken. By means of a few 36-in. drill holes, the character of the openings was determined and the effectiveness of the grouting checked. Large drill holes were useful in determining the amount of excavation necessary. In one case, question was raised as to the suitability of more than 10,000 cu. yd. of foundation rock, the appearance of the rock exposed by carefully done blasting having occasioned differences of opinion. Three 36-in. holes were drilled in the area and the examination of their smoothly cut walls proved definitely that the rock was sound and substantial. Therefore it was left in place, and the cost of removing it and replacing it by concrete was saved. The cost[5] involved was about $75,000 and the cost of drilling did not exceed $600. In all, 651 ft. of large-diameter core drilling was done at Norris at an average cost of $8.86 per foot.

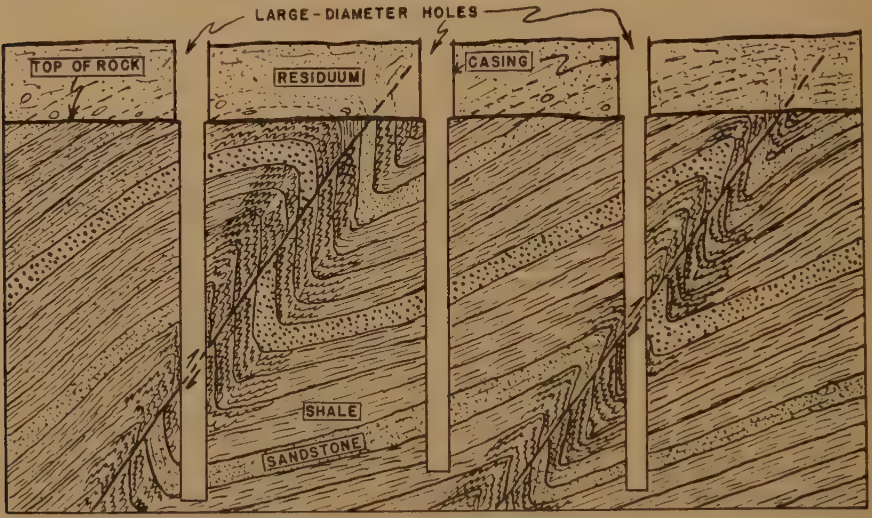

FIG. 6.—FOUNDATIONS IN DEFORMED SHALE AND SANDSTONE SERIES MAY BEST BE EXPLORED BY LARGE-DIAMETER CORE HOLES.

EXPLORATION OF MINERAL DEPOSITS

The large-diameter core drill may be advantageously used in the exploration of certain mineral deposits. Some commercially valuable minerals, such as talc (including steatite and pyrophyllite), vermiculite, bentonite, gypsum and possibly sulphur and salt, are too soft or too soluble to be successfully recovered in small-diameter cores. Moreover, other materials, such as marble, limestone and serpentine, may contain defects that may not be properly evaluated from small cores. These materials may be explored by means of large-diameter holes, if the deposits seem to be of sufficient size or value to justify the expense involved.

DISADVANTAGES AND LIMITATIONS OF LARGE-DIAMETER CORE DRILLING FOR GEOLOGIC EXPLORATION

Although its advantages as a means of geologic exploration are very great, the large-diameter core drill is not without some disadvantages. One of the greatest is the cost of drilling, which is considerably higher per foot than that of small-diameter core drilling. It is very difficult to give an approximate cost of drilling large holes, as it varies between wide extremes, depending upon the conditions under which the drilling is done. In soft but solid rock, the cost of drilling may be as low as $5 per foot, but in rocks presenting difficult drilling conditions the cost may well exceed $50 per foot. On the average, however, the cost is somewhere between the two extremes, frequently falling between $15 and $25 per foot for holes not exceeding 100 ft. in depth. The drilling cost may, in a large measure, depend upon the ability and experience of the operator.

As compared with small-diameter core drilling, the drilling of large-diameter holes is a time-consuming process. As previously stated, 6 to 9 ft. of drilling in 8 hr. is usually considered good progress, although a 2-in. hole may be drilled 30 to 50 ft. in the same period. In addition to the slowness with which the bit cuts, considerable time may be consumed between "runs" in the control of water and the extraction of the core. The equipment used in the drilling of large-diameter holes is heavy and not easily mobile, especially in a rugged region, consequently much time is ordinarily consumed in moving the rig from one hole to another.

The large-diameter core drill is best adapted to the drilling of vertical holes, and is incapable of drilling holes at angles less than 65° from the horizontal.

Although it is possible to drill large-diameter holes to depths of several hundred feet, most of the drills now in use are designed for drilling to depths of approximately 100 ft. A 60-in. hole, drilled by a specially designed drill, was successfully carried to a depth of 1125 ft.[6] It is somewhat doubtful, however, whether large holes for exploration can be economically feasible for such depths at the present, or in the immediate future.

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DISCUSSION

(E. L. Bruce presiding)

J. R. Thoenen,* College Park, Md.—Prior to 1927, Dr. Oliver Bowles conceived the idea of using the wire saw in quarrying slate in Pennsylvania, following European practice. The idea was sold to slate-quarry operators and Dr. Bowles commissioned me to set up and operate the equipment brought from Belgium.

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* Supervising Engineer, Non-Metal Mining Section, U. S. Bureau of Mines.

In order to project the wire saw into the slate, holes had to be drilled or blasted in which to set the saw standards. Accompanying the Belgian saw equipment was a drum drill used for this purpose. The following description of its operation and subsequent development of large-diameter core-drilling equipment is quoted from Bureau of Mines *Information Circular* 2851. This is of interest because it reports the first successful attempt at large-core drilling in the United States.

"The Belgian drum drill with its forged teeth using sand as an abrasive was not successful as a means of sinking standard holes. The reasons for this were, the cumbersome nature of the tool itself, the time required to move and set it, its inability to cut holes other than vertical owing to the excessive friction set up between the long drum and the walls of the hole, and the excessive wear on the cutting teeth. Failure of this equipment after repeated trials led to search for some other equipment more flexible and better suited to the problem. Officials of the Ingersoll-Rand Drill Co. became interested and through their cooperation various schemes were tried.

"An attempt was made to sink a hole by drilling a circle of small-diameter holes with an air-hammer drill mounted on a rotary arm. The webs between the drill holes were removed with a broaching tool, thus giving a circular cut. This worked satisfactorily for shallow depths but for deep holes the binding of the tools and various other difficulties made the process so slow and unsatisfactory that it was abandoned. An attempt to drill a circle of larger holes with a shot drill was likewise unsatisfactory.

Large-diameter Shot Drill Holes

"Having determined the feasibility of cutting the slate with steel shot as an abrasive albeit the failure of the above methods, it was next determined to attempt drilling holes at a single cut large enough in diameter to accommodate the saw standard and guide wheel.

"An experimental machine was next constructed consisting of a simple revolving gear-driven head so mounted on a fabricated steel frame as to allow inclination up to 45° radially in line with the long axis of the frame. Power was supplied through a sprocket and chain drive from an 11-hp. four-cylinder Continental gasoline motor mounted on one end of the frame. A hand-operated clutch built integrally with the motor allowed starting without load.

"The drill mechanism consists of a hollow steel shaft or drill rod splined to the revolving head with the key seat running the full length of the rod, or approximately 4 ft. To the lower end of the drill rod is attached, by screw thread and coupling, the cutting bit or drum varying in diameter and construction with the size of the hole to be drilled. Additional drill rods with screw couplings can be inserted between the driving mechanism and the cutting drum as the depth of the hole increases.

"As a preliminary experiment, a 20-inch diameter bit was first attached and tried. With this equipment a hole 10 ft. in depth was drilled without trouble.

"To allow ample room for the saw standard and 28-in. guide wheel, a hole at least 36 in. in diameter was necessary. As no standard tubing of this size is available, a special tube was rolled from ⅝-in. steel plate. This drum was built 30 in. long and 3 in. from the upper end was internally supported by a ⅝-in. steel circular plate or head to which the drill rod was fastened and the whole welded together.

"Six 2-in. slots 4 in. long cut diagonally toward the direction of rotation in the bottom edge of the bit were provided for freeing the drill shot.

"With this equipment ready the drill was set up in the quarry of the Colonial Slate Co. on Sept. 10, 1927.

"The hole was pitched approximately perpendicular with the plane of the split of the slate, or at 68° from the horizontal. Some mechanical trouble was encountered, as might be expected from such a roughly constructed experimental machine. The removal of the core itself presented a rather perplexing problem but was finally solved. In sequence of events the operation was as follows:

"The drum was revolved on the flat split of the slate, using sand fed by hand as an abrasive. When the drum had cut to a depth of 2 in., it was raised and steel shot placed in the cut. The drum was then lowered and the drill started at a speed of 60 r.p.m. The drum, weighing 900 lb. itself, and drill rods provided sufficient weight for comparatively rapid drilling in this quarry.

"When the drum had cut down to the limit of its internal length (when head rested on the core) drilling was stopped, the drum hoisted by chain blocks operating on a built-up pipe headframe constructed on the drill frame, and set to one side.

"Some broken pieces of core were removed but the major portion was found to be firmly attached to the solid slate. The core was broken loose, hoisted by the chain blocks, and removed in one piece. More shot was placed in the hole and drilling continued. This process was repeated each time the drill had cut to the depth of the barrel unless broken core stopped operations sooner. As the hole deepened much time was lost in removing water after lifting the drum preparatory to removing the core. After completing the hole, measurements showed the bottom edge of the drum to have been worn off ⅜ of an inch. About 20 lb. of steel shot and 20 gal. of gasoline were used.

"After completing the initial hole at the Colonial quarry the drill was taken to the quarry of the Chapman Slate Co. and two 10-ft. holes were bored. The slate here is much harder than at the Colonial and provided a much more conclusive test for the drill.

	Colonial Quarry		Chapman's Quarry	
	Belgian Drill Hole No. 1	I.R. Shot Drill No. 2	I.R. Shot Drill	
			No. 3	No. 4
Total elapsed time	45 hr.	29 hr.	40 hr.	34 hr.
Total drilling time	13 hr.	13 hr. 44 m.	19 hr. 33 m.	15 hr.
Total setting up time	25 hr.	2 hr.	3 hr.	3 hr.
Total tearing down time	1 hr.	40 min.	1 hr.	3 hr.
Total removing core time	6 hr.	12 hr. 36 m.	16 hr. 27 m.	13 hr.
Total depth of hole	78 in.	122 in.	122 in.	124 in.
Av. depth of hole per hr	7.48 in.	9.4 in.	6.24 in.	8.27 in.
Cost per foot	$8.51	$3.32	$5.31	$4.49

"This cost should be considerably lowered in future holes. It must be borne in mind that the machine with which this hole was drilled was only an experimental one and no provision was made for apparatus for either lifting the heavy core or removing the water from the hole.

"It is interesting to note here also that these holes 36 in. in diameter are probably as large if not the largest ever drilled by a shot drill."

J. T. SINGEWALD, JR.,* Baltimore, Md.—The large-diameter core drill was used for geologic exploration at the Prettyboy Dam by the Public Improvement Commission of Baltimore City in 1931. The problem that led to the adoption of this type of exploration at this dam site and the results achieved were presented before the Geological Society of America in December 1931.[7]

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* Professor of Economic Geology, Johns Hopkins University.

Unexpected conditions of unsound rock were encountered on the west abutment of the dam site that required geologic investigation. At the beginning of the excavation of this abutment, fresh rock was encountered at the expected depth of about 8 ft. below the surface. Farther west, the overburden was underlain by soft iron-stained rock in which the original rock textures were perfectly preserved, but which disintegrated on exposure and behaved like overburden. The boundary between sound rock and unsound rock appeared to be a fault striking across the axis of the dam and dipping into the hill. Because of the incompleteness of the record afforded by the cores of the 1¼-in. preliminary boreholes in the area underlain by the unsound rock, and the importance of the problem with respect to further excavation on the west abutment, it was decided to drill large-diameter holes with a 3-ft. Calyx drill. By providing drill holes large enough to permit the geologist to descend them, not only was the character of the rock itself observed more thoroughly and critically, but also the number and directions of the faults, joints, and fractures in the rock were determined. These features were recorded graphically on logs of the holes.

The rock in which these large-diameter holes were drilled is a highly quartzose quartz-mica schist.

Prior to the drilling of the exploratory holes, the contractor had already used the Calyx drill to bore large-diameter holes to enable him to excavate the east abutment with the aid of wire saws. The foliation of the schist dips at a low angle from east to west. When a line of holes was drilled and shot, much of the force of the explosion was spent in lifting the rock along its planes of foliation. It broke across those planes with greater difficulty and with a very irregular and ragged fracture. Rock that originally was sound was loosened by shooting to such an extent that it had to be removed. This condition was most pronounced on the east abutment, where the dip was toward the valley. Little success was achieved by drilling shorter holes and using smaller charges of dynamite, and excavation in sound rock was greatly exceeding what was required for the dam. The problem was solved by cutting out the excavation for the dam with wire saws instead of blasting out the rock. This was the first known use of wire saws to cut such highly quartzose rocks. Their use had previously been restricted to softer rock like slate and marble.

In a personal communication in August 1938, Irving B. Crosby informed me that large-diameter core drills have been used extensively for years at a granite quarry at Chelmsford, Mass., not for exploratory work but in opening up the quarry. This probably antedates their use in exploring dam sites.

Two novel features of the work on the Prettyboy Dam site in 1931 were, therefore, the use of wire saws in cutting highly quartzose rocks, and the boring of core drill holes 3 ft. in diameter for geologic exploration of the site.

S. H. HAMILTON,* Philadelphia, Pa.—Large-diameter core drills made by the McKernon-Terry Co. of Dover, N. J.,† were capable of taking cores and leaving a bore of about 30-in. diameter. They were in use about 1915 or 1916, especially in the coal mines of Pennsylvania for cutting airways through coal. These machines used hardened steel granules (called "shot") somewhat after the manner of the older "calyx" drill. At that time I was associated with the consulting engineering firm of

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[7] Weathering and Albitization of the Wissahickon Schist at the Prettyboy Dam, Baltimore County, Maryland. *Bull.* Geol. Soc. Amer. (1932) **43,** 449–468.

* Consulting Mining Geologist.

† McKernon-Terry large-diameter core drills were described in *Engineering and Mining Journal* about 1914.

Hamilton and Hansell, Inc., and was called upon to take a large-diameter McKernon-Terry equipment to Bangor district, Pennsylvania, by Solomon Flory. The McKernon-Terry machine quickly showed its ability to drill core holes in slate.

Later large-diameter core holes were drilled in the Bangor slate belt with bits set with "Sulmanit," a hard alloy introduced by the Sullivan Machinery Co., of Chicago. The Sulmanit was set somewhat after the principle of setting bortz or carbonado in diamond-drill bits. As the Bangor slate when free of "knots" is not hard to drill, it appeared that the Sulmanit drills were not necessary for this work.

A few years ago I went into the matter of using tungsten carbide sold under the name "Borium," with people interested in the Bangor slate district. Borium may be applied to core bits by welding and has proved very successful in the core drilling of oil wells. During recent years the Bangor slate belt has not been active and I am not informed whether Borium-shod bits have been used to any extent there.

B. C. Moneymaker (author's reply).—In the foregoing discussions, considerable emphasis is placed on uses of the large-diameter core drill other than for geologic exploration. Drills of various types, some of which were improvised, had long been used for drilling large-diameter holes for numerous purposes before their advantages in geologic exploration were recognized. So far as I have been able to determine, the first use of large-diameter borings for geologic exploration was made by Dr. Joseph T. Singewald, Jr., at the Prettyboy Dam, in 1931. Since 1931, the large-diameter core drill, especially that developed by Ingersoll-Rand, has been very widely used in the United States and abroad as a tool for geologic exploration.

The large-diameter core drill has a great many uses in addition to its use in quarry development and geologic exploration. It has been used successfully in the sinking of mine shafts, in the treatment of defective dam foundations, and in the preparation of foundations in weak rocks for piers and other heavy structures.

Use of Aerial Photographs in Geologic Mapping

By Wayne Loel,* Member A.I.M.E.

(New York Meeting, February, 1938)

The application of aerial photographs to all phases of geologic mapping is set forth, indicating the advantages to be gained in different types of country and under varying climatic conditions. Methods of field and office procedure are given from a geological point of view, as well as suggestions regarding the best methods of aerial mapping for different uses and under varying field conditions, including the study of submarine geology. Aerial photographs with accompanying geologic maps are shown to illustrate the appearance from the air of different geologic features under varying climatic and topographic conditions.

INTRODUCTION

The following paper is in no sense a contribution to knowledge; it is merely an attempt to indicate some of the benefits that may be expected from the use of aerial photographs in geologic mapping and to mention some inherent limitations. The writer has used aerial photographs in his own work for the past 13 years and has had ample opportunity to observe their use in the hands of others. From this experience certain conclusions have been drawn, which may be helpful to those using aerial photographs for the first time.

It must be remembered that a photograph of the earth's surface can delineate only that which the eye can see; therefore the geologist should not expect more from an aerial photograph than he would be able to observe were he in the photographer's airplane looking at the area to be photographed. Theoretically, if the geologist had sufficient artistic ability, he could draw as good a geologic map from his position in the plane as he could from observation of the photograph. Practically this cannot be done because the airplane moves at a high rate of speed, which in itself prohibits detailed observation and, no matter how great the geologist's artistic ability, he could not reproduce the detail that can be recorded by a camera.

An aerial photograph is a picture map of an area. The picture may be studied in the office until the geologist is thoroughly familiar with every minute detail of the surface of the ground he is about to geologize. If it is an area underlain by sedimentary rocks, much may be learned

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* Consulting Geologist and Engineer, Los Angeles, Calif.

regarding outcrops and structural conditions; or if it is an area of igneous rocks, the general outline of masses of different types of rock can often be observed, as well as dikes, veins and faults. All of this, together with means of access such as roads, trails, navigable streams, and open areas in heavily vegetated regions, make the aerial photograph almost indispensable in geologic work today.

On the other hand, with all its wealth of detail, the aerial photograph is not an absolutely accurate map, since a photographic lens records objects on the film in perspective and does not reduce them to their true positions, vertical to a given horizontal plane, as is done in mapmaking. Thus, if we have a picture covering a level area with a ravine cutting it near one edge of the photograph and a hill rising near the opposite edge, we will find, by measuring between objects in the ravine, on the plain, and on top of the hill that the relative distances measured between the images of the same objects in the photograph are not constant. In other words, the scale of the photograph changes in proportion to the elevation of the objects measured, being greater on top of the hill than in the ravine.

In addition to this, it will be observed that horizontal distances measured from a point in the center of the photograph to objects having different ground elevations will not be constant with the relative distances as measured to the corresponding photographic images. The ground measurements to points below the elevation of the central point will be greater in proportion to the photographic distances, while those to points of greater elevation will be less.

This would seem to greatly restrict the usefulness of aerial photographs in detailed mapping but, unless the differences of elevation are very great and the accuracy of mapping required is of an unusually high order, such differences in scale and displacement of image can be disregarded.

REQUIREMENTS OF AERIAL PHOTOGRAPHIC MAPS FOR GEOLOGICAL USE

In contemplating the use of aerial photography for geological work, it must be borne in mind that aerial photographs are not in themselves geologic maps. The aerial photograph may show much geology or it may show almost none, depending on the type of rocks involved, the climatic conditions, and the vegetation. In some instances aerial photographs show so little geology that they are valuable only as good detailed maps of the country to be worked, but even under such circumstances they are far superior to any other type of map, since the minute details of topography and vegetation shown in the photograph enable the geologist to locate himself at all times with great accuracy.

Before geologizing any territory, the geologist should make a reconnaissance by airplane, because in that way an excellent idea can be obtained of the general terrain and such broad geologic features as may be observable from the air. In the course of such a flight careful note should be made of color and lighting effects at different times of day, so that the subsequent photographic work may be done to the best advantage. The wide range of color filters used in stationary photography is not available, because the photographic plane travels at a speed of more than 100 miles per hour and shutter speeds less than one one-hundredth of a second will blur the image. For this reason the darker filters, which best accentuate slight color variations, cannot be used. The filters that can be used, however, give surprising results sometimes and always tend to brighten the image that would otherwise be dimmed by the presence of haze or dust in the atmosphere.

In any type of photography, light plays a principal part in obtaining sharpness and brilliant definition. The time of day, time of year, and the latitude of the country to be photographed must all be taken into consideration. In latitudes north of 40° north latitude aerial photographs should not be taken when the sun is in its lowermost declination, since at such times shadows are very pronounced even at noon. On the other hand, pictures taken at noon when the sun's declination is high lack contrast, and topographic detail appears flat and featureless even in country of fairly bold relief.

If the geologist has the opportunity to view the country from an airplane before it is photographed, he will be able to observe the time of day when light conditions are best for mapping the particular area. If part of a map is flown during the morning hours and another part in the afternoon the shadows will have shifted and a most peculiar topographic effect is obtained. From 10:00 to 11:30 o'clock in the morning and from 12:30 to 2:30 o'clock in the afternoon are usually the best hours for aerial mapping. If the steeper slopes in general face the west, the afternoon should be chosen for photographing, and vice versa. It is difficult to photograph a brightly lighted slope and one in deep shadow so that the details of both may be clearly seen; hence, where the topographic relief is great, a time of day must be selected when no deep shadows will appear.

At certain times of the year in the northern latitudes the sun's declination alone will cast sufficient shadow so that photographing can take place continuously from eleven in the morning until two in the afternoon. In countries of very low relief the topography stands out better by photographing either earlier in the morning or later in the afternoon.

Such curtailing of flying time might seem to increase the cost unduly, but since it is possible to do fairly large-scale mapping at from 150 to 400 square miles per hour, the smaller jobs may be completed in less than two hours of flying time.

In many parts of the country the time of year is important by reason of the condition of vegetation. Usually the green vegetation in the spring will mask much of the soil coloring. As the season progresses areas of various types of rock may be revealed progressively by the different forms of dying vegetation, the habitat of which is limited to the soil derived from such rocks. In the summer months color differences in soil and rock are usually noticeable, but in the winter these are changed and often obliterated by moisture.

Successful mapping cannot be done during cloudy weather, because clouds below the plane appear as white areas on the map, while the shadows of clouds above the plane photograph as dark areas in which no detail is visible. No aerial mapping should be attempted when there is snow on the ground.

Two types of photographic cameras are in common use in the United States today: the single-lens camera taking a picture 7 by 9 in. and the multilens camera having four or more lenses. The most widely used multilens camera is the four-lens type having a 5-in. focus and taking a picture approximately 10 in. square. For all types of reconnaissance work and for country where the relief is moderate the four-lens camera is more suitable. The usual scale for such work is 2 in. to the mile, with one picture covering 25 sq. miles. In country of very bold relief, the photographic distortion toward the edges of the picture is sufficient to become annoying, but since maps are usually flown with a generous overlap from one picture to the next the extreme edges of the photograph need not be used. The single-lens camera is universally used for large-scale detail work because it is possible to reduce photographic errors to a greater extent with this type than with the multilens type By flying at a high altitude with a long-focus lens a large-scale picture can be obtained with comparatively little distortion even in country of rather bold relief. In specifying the type of camera and scale of picture to be used, these factors should be kept in mind together with the surface elevation of the terrain to be photographed, since it is not practicable to fly photographic planes at elevations much greater than 24,000 ft. above sea level.

The making of mosaic maps is simplified and is more satisfactory when the single-lens camera is used, by reason of the lessening of distortion. However, the cost of photographing with a multilens camera is considerably less and is frequently quite satisfactory, although it must be obvious that, with the wide angle of view obtained by use of this type of camera, there is less map accuracy and more of a pictorial effect as the edges of the picture are reached.

Use of Photographs in Field Work

Most geologists in the United States prefer the single 7 by 9-in. picture for use in the field, although the four-lens 10 by 10-in. photograph is beginning to be used to some extent. Prints mosaiced into map form are not greatly in favor for field work since it is almost impossible to match adjoining prints without overlapping or loss of image in one or the other. This is due to the divergent displacement of the two images of the same point in the adjoining photographs. This condition is not particularly noticeable in flat country but in areas of sharp relief the lack of continuity becomes very objectionable. An accurate mosaic can be made but a large amount of ground control is required and the cost is high. In addition to this the building of an accurate mosaic requires a considerable amount of time, which is an added delay in starting the geological work.

Most aerial mapping is done in such a way that there is a large overlap from one picture to the next, the overlap being greater in the direction of flight than between adjoining strips. The overlap between individual pictures in a strip is usually 60 per cent. The purpose of this is to facilitate the use of the stereoscope in the examination of the separate prints. By reason of the large overlap the prints in a single strip may be trimmed and placed edge to edge with no visible displacement or loss of image from one print to the next. These cut-out prints may then be mounted on cloth with a sufficient distance between the adjacent edges to permit folding. If the job is well flown the strips will match fairly well from one to the other and may be laid side by side for a study of the area as a whole. This method is usually sufficient for general geologic mapping.

If greater accuracy is desired a skeleton network of ground control may be put in by triangulation and leveling, with which, by using photogrammetric methods, the mapping company will be able to trace the rock contacts and other geologic data directly from the prints in such a manner that all photographic distortion is eliminated. In this way a true and accurate geologic map is obtained. Should such work be desired it is advisable to consult with the mapping company in advance regarding the amount and nature of the ground control.

Before using aerial photographs in the field two things should be established: the direction of true north and the scale of the photograph. It is customary to draw a north-south line directly on the print. This may be done by taking the magnetic bearing from one prominent object to another some distance away and making the proper allowance for local declination. The points selected should have as nearly as possible the same elevation. Any line connecting any two other points in the same photograph having equal elevations will then have a correct azimuth relative to the established north-south line. In this regard it must be remembered that all points in an aerial photograph having the same elevation are correctly shown relative to each other but not relative to points of either greater or less elevation.

For determination of scale it is necessary to measure by tape or stadia between two prominent objects at equal elevations on each photograph.

Usually a mean datum plane is selected for the entire area and all measurements are made at this elevation.

In aerial photographs the images of objects are displaced from their true positions radially from the center of the photograph according to the equation:

$$D = \frac{rd}{A}$$

in which D = amount of displacement measured in inches on the photograph. If the object is above the datum plane D is plus; if below, D is minus.

r = distance of displaced image from center of photograph in inches.

d = difference in elevation between object and datum plane, feet.

A = height of camera above datum plane, feet.

Therefore, if the camera is at 12,000 ft. above the mean surface or datum plane, the image of the object is 3 in. from the center of the photograph, and the object is 500 ft. above the datum plane; then:

$$D = \frac{3 \times 500}{12{,}000} = \frac{1}{8}$$

The displacement in this case is plus, which means that the image is ⅛ in. farther from the center of the print than the true scale distance.

From these figures, it will be seen that in general such displacement of points in the photograph away from their true position is not of sufficient amount to be readily noticeable and is usually disregarded in geologic mapping.

When contour lines are necessary to the delineation of the geology, such contours may be placed directly on the photographic print in the field by any of the methods in common use in topographic mapping. For instance, if great accuracy is not needed a hand level, altimeter, Brunton compass, or a combination of all three, may be used to advantage. Should greater accuracy be desired, a surveyor's level, transit or alidade and plane table may be used. In areas of low relief the latter instruments are preferable and it is then necessary to employ the services of a rodman. It is desirable that the instrumentman and rodman each be supplied with prints covering the area, so that each may indicate on the print the various positions he has occupied.

In areas of sufficient relief, where the instrumentman may sight directly to objects on the ground, stadia measurements need not be taken because the distance may be scaled with sufficient accuracy directly from the print. If such work is done with a plane table, using the print as a plane-table sheet, the photographic displacement of objects will be immediately noticeable. The blade of the alidade will not fall on the image of the object sighted through the telescope unless the point sighted is at the same elevation as that at which the instrument is set up. If photographs for such use are taken from an elevation sufficient to minimize the photographic distortion, and large vertical angles are avoided, a very credible topographic map can be made by an instrumentman alone using light plane-table equipment. In many instances the geologist himself does his own contouring, using the hand level or the Brunton compass. Similar topographic work can be done using the mosaic as a base map, but under such circumstances the mosaic should be assembled with a sufficient amount of ground control to assure the horizontal accuracy desired.

If a topographic map of extreme accuracy is needed in regions where the vegetation is sparse, the photogrammetric method should be used. The principle involved in this method is the stereoscopic effect obtained by viewing in a photogrammetric machine two photographs covering the same ground area but taken from different positions along the line of flight, such as two adjacent photographs in an ordinary flight strip. When the machine is properly adjusted, a small black dot appears in the line of vision of the observer. The plane in which this dot moves may be adjusted for any contour interval. Movements of the dot are transferred mechanically to a pencil that traces the contour lines on a separate sheet of paper as the operator causes the dot to move along the apparent surface of the ground. The accuracy of such contouring is directly proportional to the scale of the photograph. The ground control necessary for such work must consist of at least three points on each photograph, the exact horizontal and vertical position of which is known. It is desirable to have the mapping company place such control because it knows exactly what is necessary for accurate results. If the geologist is equipped with such a contour map and the accompanying photographs he then has at his disposal all that aerial photography has to offer.

Clues to Geology That May Be Seen in Aerial Photographs

Long before the first aerial photograph was taken, geologists were guided in their field work by physiographic and other surface evidence that might give a clue to the underlying geological conditions; therefore, in making a reconnaissance of an unknown area for the first time they sought elevated positions from which such conditions might be most readily observed. The airplane or the aerial photograph merely provides an elevated observation station, which can be moved at the will of the observer to any position he deems desirable for the observation of surface conditions. The greater the distance above the earth the greater the perspective and the more generalized the viewpoint that may be obtained.

In different parts of the country, under varying climatic conditions, the same rock types take on different aspects from the air due to different types of weathering and to differences in physiographic form. For instance, in a fairly well watered region wherein the topographic relief is not great, a granite area may not be readily discernible from one of sedimentary rocks. This is due principally to the fact that under such conditions soil accumulates to considerable thickness, rocks do not crop out frequently, and when they do the outcrops occur either in the bottoms of ravines or are confined to small patches, which are not readily recognizable from the air. Under the same climatic conditions, in areas of bold topographic relief, igneous rocks usually are characterized by sharp, rugged outcrops scattered promiscuously over the terrain, while sedimentary beds usually are distinguishable because of the differential weathering of various strata or vegetational differences. It is seldom possible in such regions either to differentiate various types of igneous rocks or different ages of stratified rocks.

It is a well-known fact that certain types of plants, bushes and trees grow more abundantly in soil derived from certain types of rocks than in that from others, but usually the mixture of mineral constituents in the soil covers so wide a band along the contact between the underlying rocks that anything approaching accuracy of geologic mapping by such observations is impossible. In arid regions, where the bare rocks are exposed and the soil covering is very thin, the difference in color between the various rocks and soil is usually more pronounced than are the vegetational changes.

In mapping an area where aerial photographs are to be used, the geologist should first acquaint himself with the appearance of the surface overlying known types of rocks, both from ground observation and from the air in the particular area in which he is to work. He will note certain peculiarities, which subsequently can be followed in the aerial photographs, and in this way will be enabled to proceed with his mapping far more rapidly, since he will know with a fair degree of accuracy in advance where and to what extent the various prominent rock types occur.

Great care must be exercised in the use of aerial photographs in the office without field reference, since soil creep may cause the apparent displacement of beds, landslides may change the attitude and position of considerable areas of outcropping strata, and frequently the same type or apparently similar types of vegetation may occupy different strata because of changes in porosity and moisture content, so that the tracing of a bed on an aerial photograph without reference to the actual outcrop in the field is an extremely hazardous procedure and should not be undertaken except for the determination of points for field observation.

Outcrops of rocks may be located and traced through fairly heavy vegetation by the use of aerial photographs in the field where such work would otherwise be extremely tedious, necessitating the meticulous following of the outcrops on the ground with difficult traveling through brush and, in some cases, the cutting of a trail. From a careful study of the photograph the contiguity of beds can often be traced after visiting a few accessible localities where the strata crop out or where cross sections may be studied. In this way the geologist may often construct a satisfactory map without tracing the entire outcrop of any bed. This frequently saves the cost of the aerial survey many times over, in time saved by the field party.

The dip and strike of strata may sometimes be observed with a fair degree of accuracy in the photograph, but owing to lack of knowledge regarding the exact configuration of the surface such observations may frequently be misleading and should not be relied upon without field examination, except for a general idea of the structural conditions.

Lines of faulting expressed in the topography may often be more readily followed in an aerial photograph than on the ground, while faults that bring rocks of different types into juxtaposition are also easily observed, providing the rock types are evidenced photographically by reason of peculiarities of weathering, differences in color, or vegetational differences. Dikes, veins or other sharply defined rock masses are usually readily discernible in the photograph.

Abandoned river courses frequently photograph well, especially oxbows and ancient river courses of which the gravel beds have been covered by flows of volcanic material, such as the Tertiary rivers in the Sierra Nevada Mountains of California. Old stream beds are often readily observable on the surface of the ground, but in many instances have been so obliterated by either vegetation or erosion as to be distinguishable only from the air. The course of subterranean rivers can sometimes be followed in aerial photographs by lines of sink holes such as occur in areas underlain by limestone rocks. Salt domes like those occurring along the Gulf Coastal plains of the United States often stand out in sharp contrast to the surrounding country, principally by reason of soil and vegetational differences.

A form of aerial geologizing not yet in common use, but which offers intriguing possibilities, is that which may be done by photographing areas covered by water. Along the Pacific Coast, off-shore oil structures have been observed by this method and there are doubtless many instances where similar observations would prove of value. In such work it is necessary that the rocks composing the sea or lake floor be not obscured by sediments. Where the bottom is predominantly sandy the position of hard reefs may often be observed by the kelp growing on them. To determine the true position of such rocks, it is necessary that the photographs be taken on a day when there is no wind or ocean swell to disturb the kelp, which normally rises vertically from its roots, otherwise the photograph will show only a confused mass rather than the structural outlines sought.

ILLUSTRATIONS

In the accompanying plates an attempt has been made to illustrate various geologic features as they appear in aerial photographs. In selecting suitable material, it was thought desirable that examples be chosen from areas wherein the geology had been published, so that more detailed geological descriptions would be available than could be given in a paper of this scope. It was found necessary to include considerable areas in some instances to show the more extended geologic features. This resulted in very small-scale reproduction of the original maps, which detracts much from the value of the photographs.

In order to compensate for this, arrangements have been made with the aerial mapping firms through whose courtesy the various photographs are reproduced to supply members of the Institute with original photographs of the areas illustrated at a cost of one cent per square inch.

Thus it will be possible for those interested to study the original large-scale photographs in conjunction with the published geologic maps and descriptions of the areas shown.

From a study of this kind more may be learned regarding the value of aerial photographs in relation to geologic mapping than under any other circumstances except by their actual use in the field.

Because most people are able to see the topography in aerial photographs to better advantage when facing the shaded slopes, it is suggested that the photographs be inverted and viewed from the north rather than in the customary manner. For convenience of reference, numbered and lettered coordinates have been placed along the edges of the geologic maps. It is regretted that no suitable illustration is available at this time showing subsea photography.

FIG. 1.—CLIFTON-MORENCI AREA, ARIZONA.

This area is one of very complex geology, in an arid region, wherein both igneous and sedimentary rocks are involved. The principal igneous rock exposed is granite, with secondary amounts of granite-porphyry, quartz-monzonite-porphyry and diorite-porphyry. In addition to these deep-seated rocks there are notable flows of andesite, basalt and rhyolite, with numerous dikes of the same materials. There is also a good representation of sedimentary rocks ranging in age from the Gila conglomerate (Quaternary) to the Coronado quartzite (Cambrian), as well as the metamorphosed Pinal schist (pre-Cambrian).

A description of all of the details of structure and the various rock formations that may be observed in this photograph would be tedious, but some of the more important features may be pointed out. The western portion of the map exhibits rocks mainly of a granitic type, with numerous fault blocks of older sedimentaries. The most striking feature in this area is the Coronado vein seen at D-1 to 3. The magnitude of the fault in which this vein is formed is evidenced by a drop of the Coronado quartzite block to the south of approximately 1200 ft. In the eastern portion of the area the flow rocks are the features most worthy of note. At B-10, for instance, the flat-lying rhyolite flows take on the aspect of sedimentary beds, while the adjacent Gila conglomerate at B-9 and southward along the west bank of the San Francisco River looks exactly like the basaltic area on the east bank of the river. This is a good example of the possibility of being misled by aerial observation alone. Northeast of the town of Clifton is a roughly triangular, light colored area, which is rhyolite but bears no resemblance to the area at B-10.

The darker mass abutting against the rhyolite to the southwest is andesite, and a dark mass to the east is the Morenci formation, composed of black shales and argillaceous limestone. Where a tongue of the Morenci formation juts into the rhyolite mass from the east it does not appear as dark as the main mass. In the southern portion of the aerial map the white areas are the dumps from the mines at Morenci.

The geologic outline map is taken from U. S. Geol. Survey Folio 129. The geology of this area is described by Waldemar Lindgren.[1]

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[1] References are at the end of the paper.

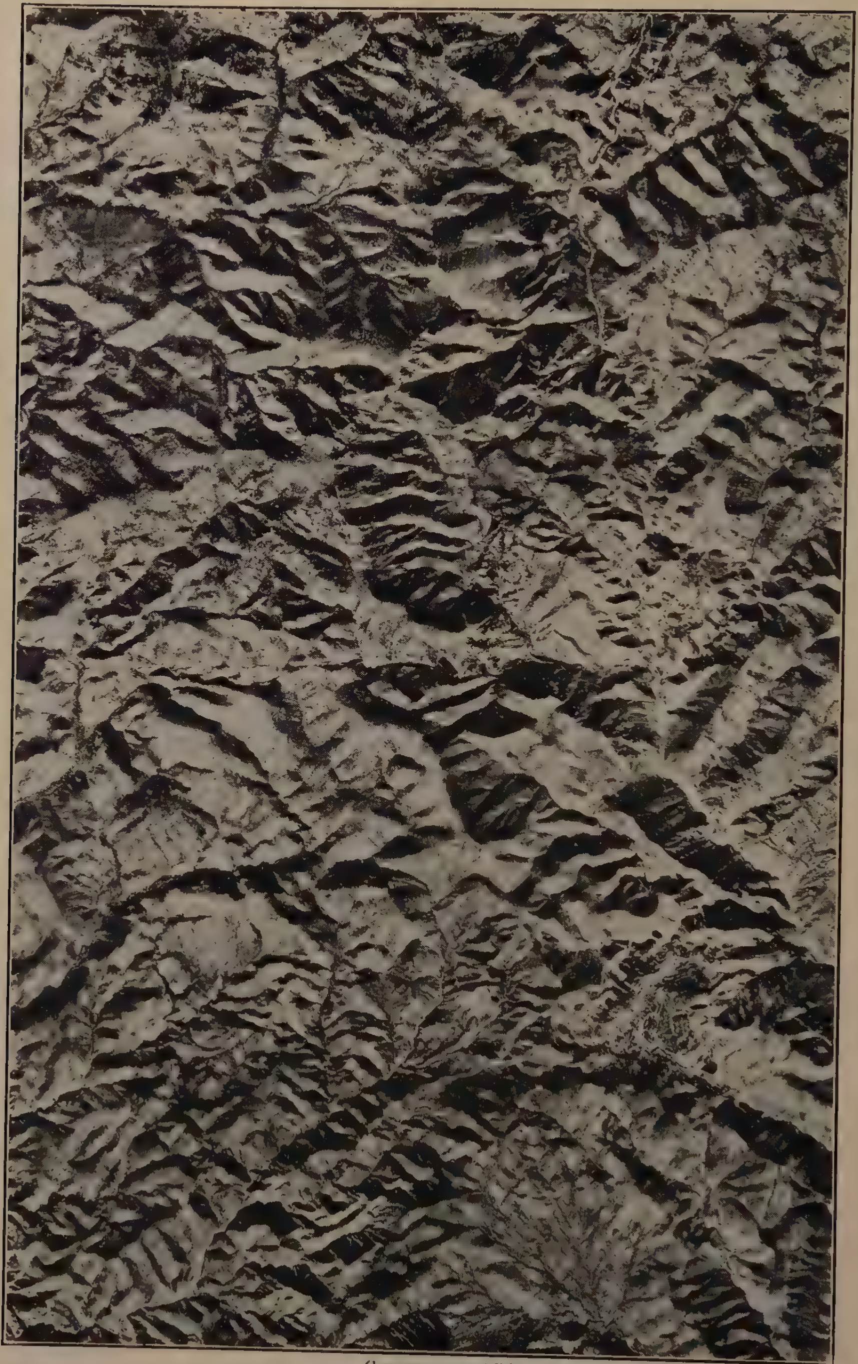
LEGEND

SEDIMENTARY ROCKS

Quaternary	*Qal*	Alluvium	Sand and gravel along present valleys, and local talus accumulations
	Qg	Gila conglomerate	Thick fluviatile deposits of irregularly bedded conglomerate and sand, locally consolidated
Cretaceous (Benton Group)	*Kp*	Pinkard formation	Alternating brown sandstone and black shale; hardened and metamorphosed near porphyry contacts
Carboniferous	*Ct*	Tule Spring limestone	Heavy-bedded bluish gray limestone in northern part of quadrangle; contains Mississippian and Pennsylvanian fossils
	Cm	Modoc limestone	Heavy-bedded gray limestone, sometimes magnesian in lower part; contains Mississippian fossils
Devonian (?)	*Dm*	Morenci formation	Black clay shale with argillaceous limestone locally in lower part
Ordovician	*Ol*	Longfellow formation	Heavy-bedded brown limestone, shaly and siliceous in lower part; usually cherty and sometimes magnesian
Cambrian (?)	*Ꞓc*	Coronado quartzite	Brown and red quartzitic sandstone, usually with basal conglomerate
Pre-Cambrian	*ps*	Pinal schist	Sericite-quartz-schist containing small masses of amphibolite

IGNEOUS ROCKS

Tertiary	*Ta*	Andesite	Surface flows and dikes, representing two epochs of eruption
	Tb	Basalt	Thick, dark colored surface flows, rarely tuffaceous; represents two epochs of eruption
	Tr	Rhyolite	Thick, light colored surface flows with much tuff and breccia; represents three epochs of eruption
	Tr, Tb, Ta		Dikes of rhyolite, basalt, and andesite.
Late Cretaceous or early Tertiary	*gp, db*	Granite-porphyry, quartz-monzonite-porphyry, and diorite porphyry	With transition phases; occur in dikes, stocks, and laccoliths; also dikes of diabase, *db*
Pre-Cambrian	*gr*	Granite	Intrusive masses in Pinal schist



Courtesy Fairchild Aerial Surveys, Los Angeles, Calif.

FIG. 1.—CLIFTON-MORENCI AREA ARIZONA.

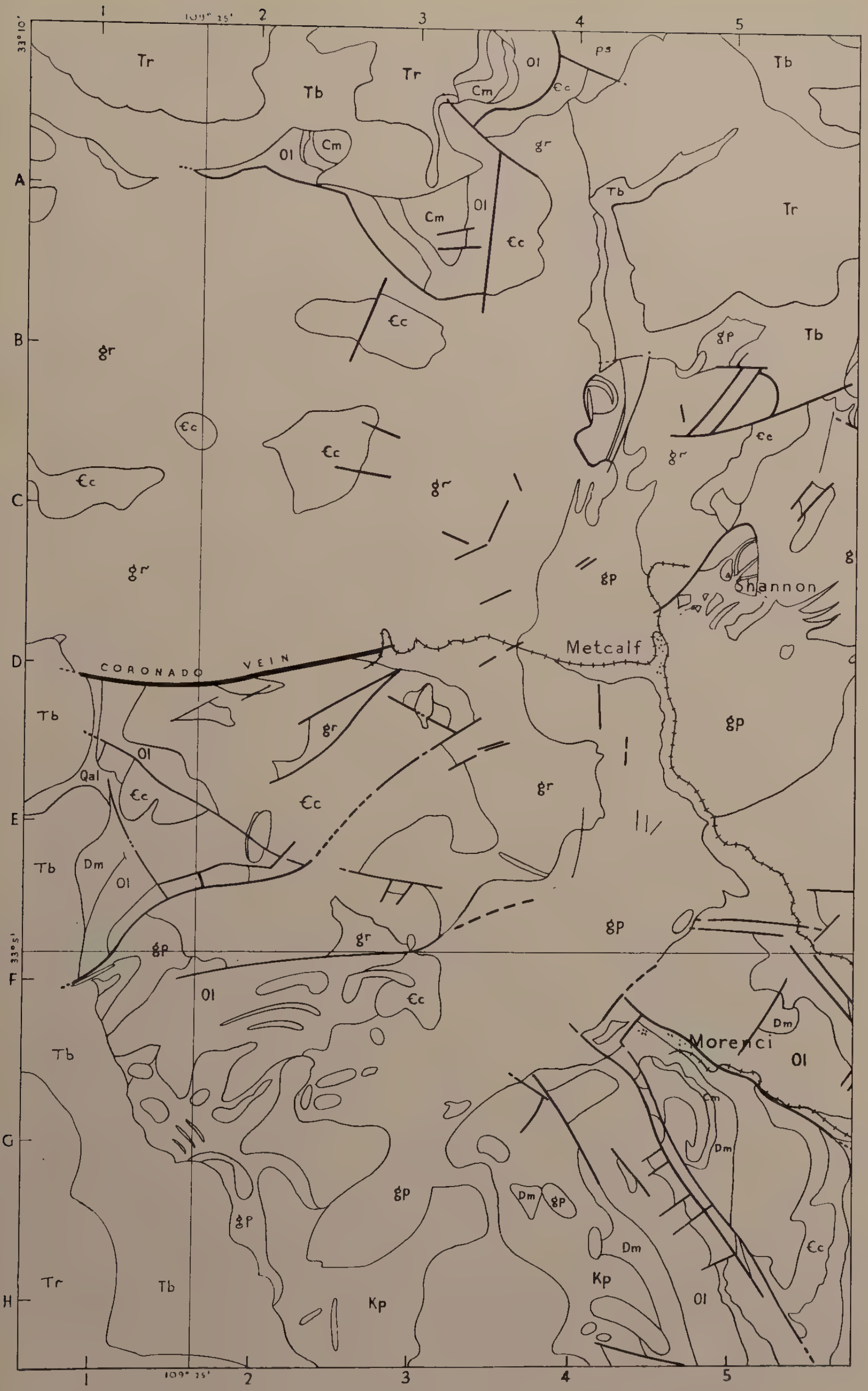


FIG. 1.—*(Continued)*

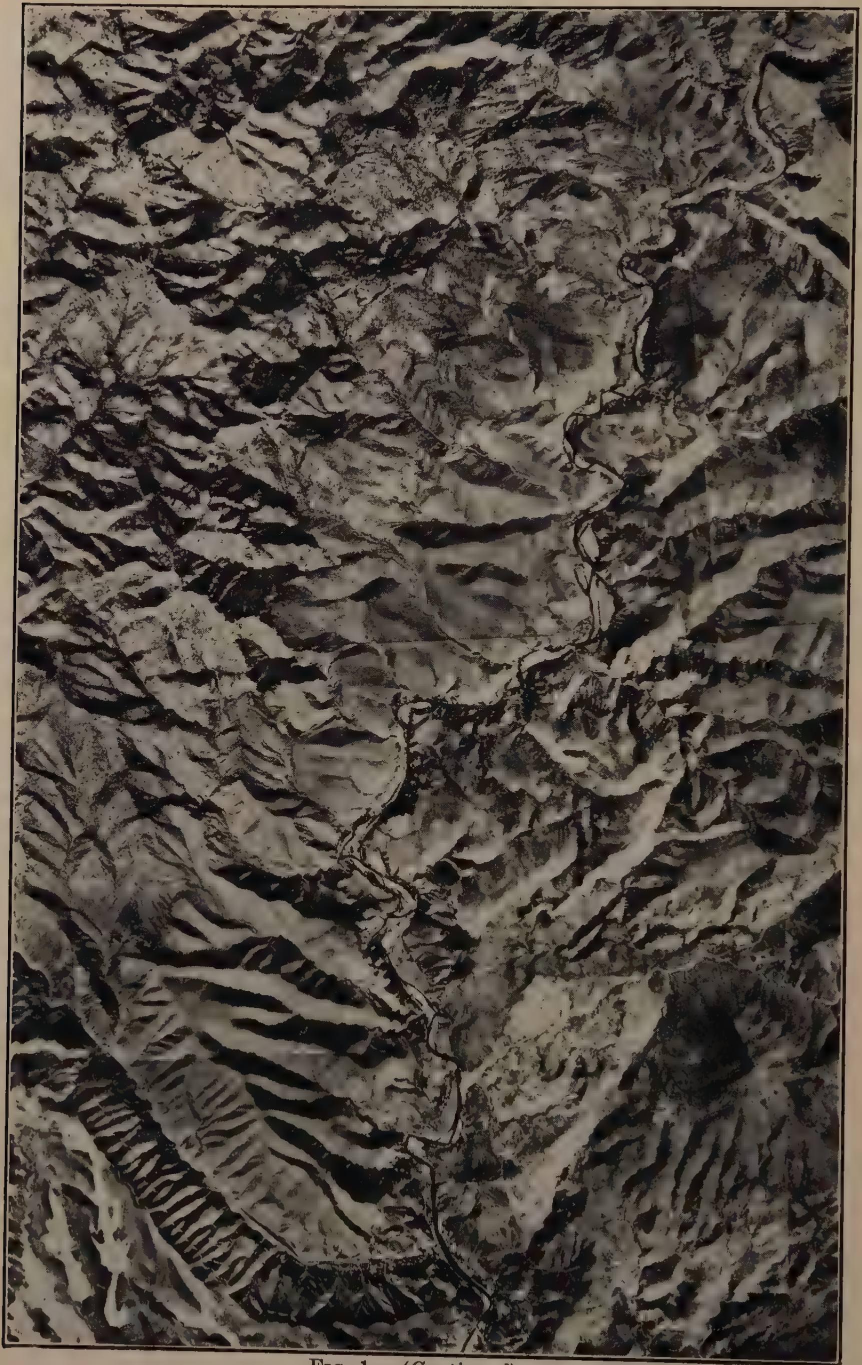


FIG. 1.—(*Continued*)

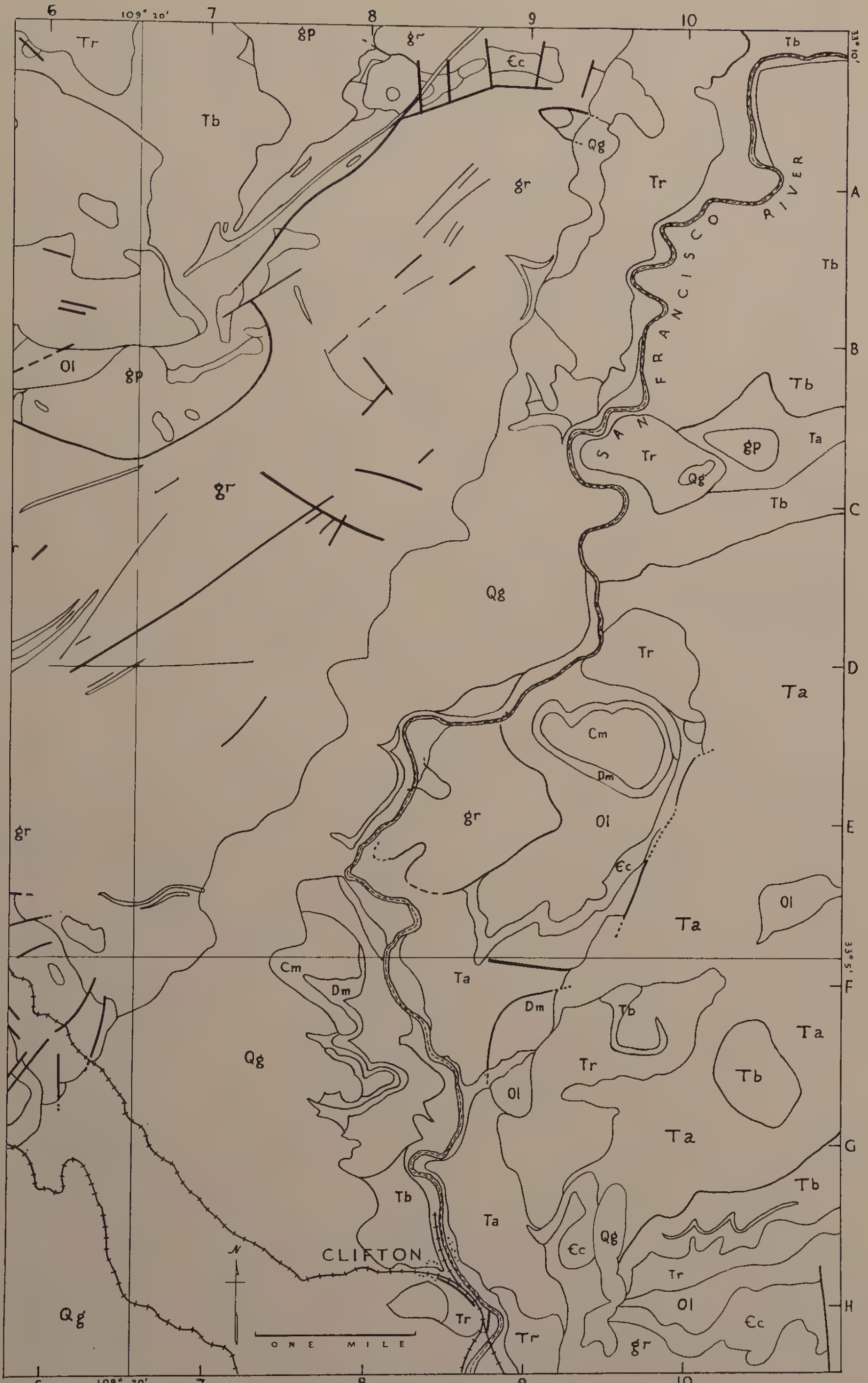


FIG. 1.—*(Continued)*

Fig. 2.—Ray Area, Arizona

The area shown in this plate lies in the southwestern part of the Ray Quadrangle, Arizona. The aerial mosaic was extended a little beyond the boundary of the quadrangle to show some diabase intrusions just off the southwestern edge of the sheet, as well as some quartz-diorite prophyry dikes just north of the Gila River, along the western boundary of the quadrangle. This area has been chosen as representative of what the geologist may observe in aerial photographs in the arid mining regions of the southwestern part of the United States, particularly in Arizona and New Mexico.

The central portion of the area is occupied by a recently uplifted mass of granite, which has been weathered into sharp relief, forming the crest of the Tortilla Mountains. The appearance of this granite area should be contrasted with that in the southwestern corner of the photograph, where the relief is low.

The Gila conglomerate covers most of the area not occupied by granite and is typical in its appearance both along the eastern edge of the Tortilla Mountains where the beds are steeply tilted and in the valley floors where the strata lie nearly flat. With the exception of the Gila conglomerate the only sedimentary formations present are the steeply tilted strata in the extreme southern portion of the quadrangle, readily observable in the photograph.

The principal points of interest from an aerial photographic standpoint are the various intrusions into the granitic mass and a line of faulting not shown on the geologic map except where two formations are brought in contact by the fault. First, it should be noted that where the diabase has intruded the granite, either in the form of a massive intrusion or as thin dikes, the outline of the darker rock is easily traceable. For instance, the dikes lying in the vicinity of H-1 and westerly are extremely well marked, as is also a part of the intrusion shown at A-1. The contrast in other parts of the area is not so marked in the small scale of the map as reproduced, but the different rocks are readily distinguishable in the contact prints from which the map was made.

In the extreme northwestern part of the area occur a number of east-westerly trending quartz-diorite porphyry dikes observable in the photograph as white lines against the darker country rocks. In the south central portion, at G-2-4, a group of similar dikes cuts the granite and are topographically prominent.

At E-F-3-4 there is a north-south fault that brings a small area of Tornado limestone (Carboniferous) to the surface through an area of Gila conglomerate, the fault being the western boundary of the limestone area. On the geologic map this fault was not extended beyond the boundaries of the limestone, but its continuation as observed from the aerial photograph has been dotted. The fault may be readily traced northward to the bend in the Gila River at Erman and thence possibly across the river into the small diabase dike shown at that point. In arid regions, faults and other lines of dislocation may often be traced in this manner by topographic indications on an aerial photograph, where it would be extremely difficult, if not impossible, to do the work on the ground without a photograph.

The geologic map accompanying this plate was taken from U. S. Geol. Survey Folio 217. The geology has been described by F. L. Ransome.[2]

LEGEND

SEDIMENTARY ROCKS

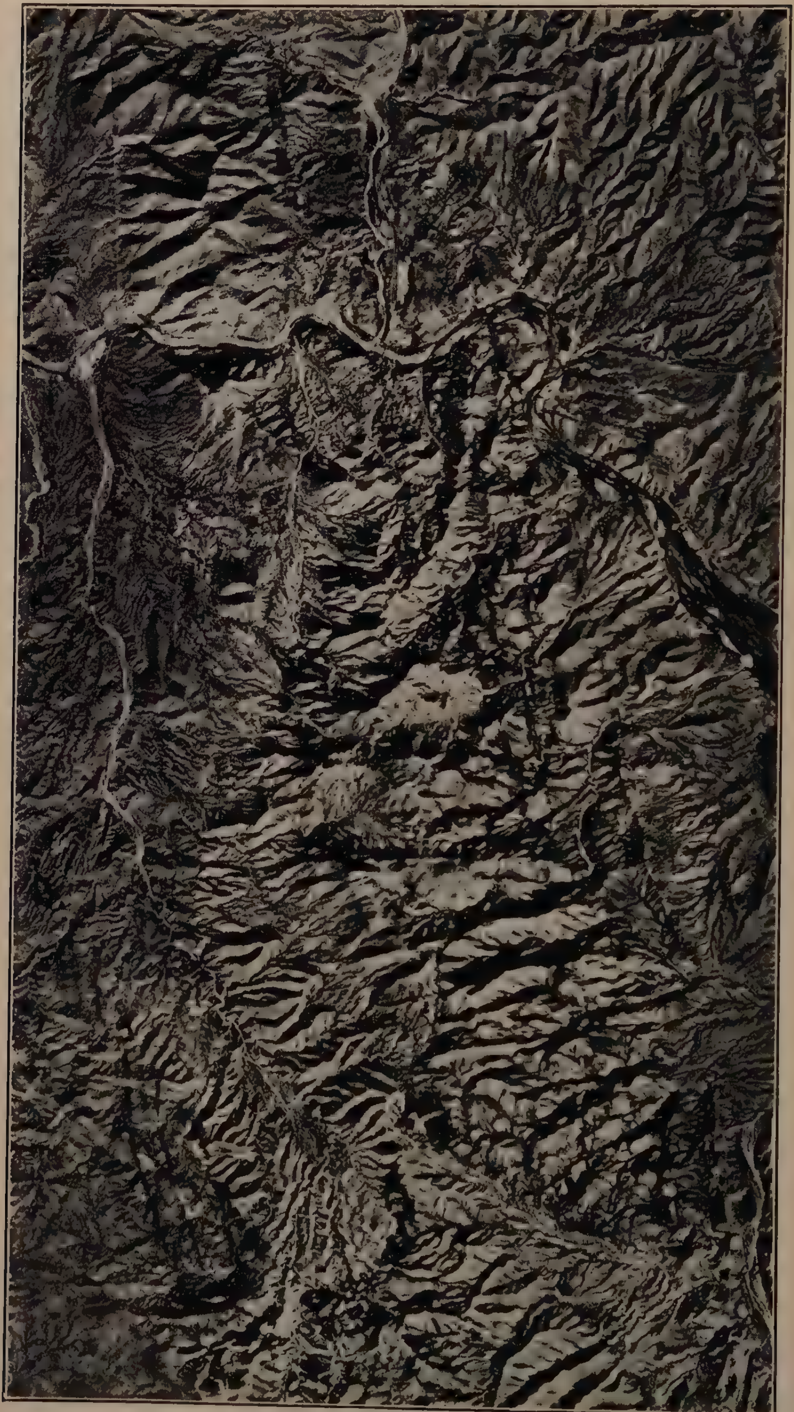
Quaternary	*Qal*	Alluvium	Gravel, sand, and silt along present streamways
	Qg	Gila conglomerate	Fluviatile conglomerates, coarse in places near the mountains, grading into fine silts, probably in part lacustrine, in wide valleys; includes some beds of tuff and infusorial earth
(Unconformity)			
Tertiary	*Tw*	Whitetail conglomerate	Subangular fragments chiefly of diabase and limestone accumulated by streams and hillside wash
(Unconformity)			
Carboniferous	*Ct*	Tornado limestone	Light gray limestone thick bedded in lower part, thinner bedded in upper part. Fossils abundant in upper beds
Devonian	*Dm*	Martin limestone	Thin-bedded, yellowish to dark gray, somewhat magnesian limestone; upper part fossiliferous; some yellow arenaceous beds in lower half
(Unconformity) (?)			
Cambrian and possibly also Ordovician and Silurian	*Ꞓt*	Troy quartzite	Cross-bedded pebbly quartzite, chiefly thick bedded, but thin flaggy beds, marked with worm casts, in upper portion
	Ꞓm	Mescal limestone	Thin-bedded, white to buff limestone, in part dolomitic, with abundant knotty layers of chert. Includes, as mapped,

			an overlying flow of vesicular basalt
	Ꞓds	Dripping Spring quartzite	Fine-grained, ripple-marked and sun-cracked, arkosic quartzite, much of it banded dark red and gray
	Ꞓb	Barnes conglomerate	Coarse, well rounded quartzose, pebbles in arkosic matrix
	Ꞓp	Pioneer shale	Dark, reddish brown, spotted with yellow, arenaceous shale, grading into arkosic quartzite at base. Includes, as mapped, underlying thin Scanlan conglomerate
(Great unconformity)			
Pre-Cambrian	*ps*	Pinal schist	Chiefly fine-grained quartz-serecite schist; metamorphosed fini-arkosic sediments. Includes some metamorphosed grits and a little schistose igneous material

IGNEOUS ROCKS

Late Tertiary (?)	*Td*	Dacite	Thick extensive flow with a little tuff at base; in northwestern part of quadrangle
Early Tertiary (?)	*Tr*	Rhyolite porphyry	Rhyolite porphyry dikes east of Tam o'Shanter peak
	Tqdp	Quartz diorite porphyry	Dikes and small intrusive masses, particularly abundant near Troy and Tornado peak
	Tgd	Granodiorite	Intrusive mass in Troy Basin
	Ttm	Teapot Mountain porphyry	Dikes and irregular intrusive masses of quartz-monzonite porphyry near Ray
	Tgm	Granite Mountain porphyry	Irregular intrusive masses of quartz-monzonite porphyry near Ray
	Tqd	Quartz diorite	Dikes and comparatively small intrusive masses
Cretaceous (?)	*Ka*	Andesite tuff and breccia	Chiefly consolidated pyroclastic material with contemporaneous dikes; possibly includes some lava flows
Mesozoic (?)	*db*	Diabase	Typically a medium grained ophitic, olivinitic diabase or dolerite. Irregular sills with many crosscutting connections; intruded especially in the Mescal limestone

Pre-Cambrian	*md*	Madera diorite	Quartz-mica diorite, apparently grading locally into granodiorite or quartz monzonite; in places gneissoidal. Irregular batholithic intrusions in the Pinal schist of the Pinal Range
	gr	Granite	Biotite granite, generally coarsely porphyritic and crumbling. Batholithic intrusive mass extensively exposed in the Tortilla Range



Courtesy Fairchild Aerial Surveys, Los Angeles, Calif.

FIG. 2.—RAY AREA, ARIZONA.

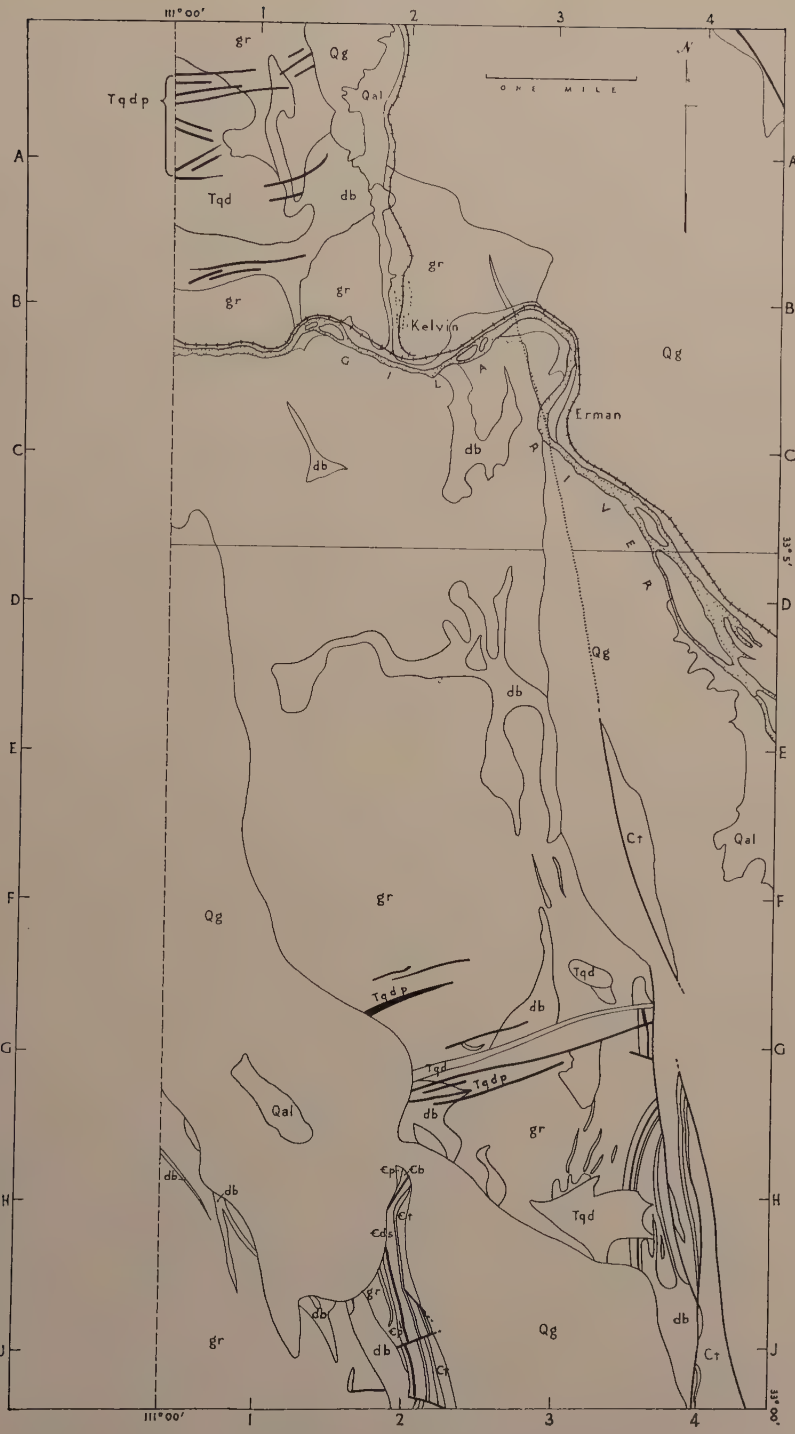


FIG. 2.—(*Continued*)

Fig. 3.—Silver City Area, New Mexico

This area, extending northerly from Silver City, N. M., shows the marked differences that frequently exist in semiarid regions between various types of sedimentary rocks. Beginning at Silver City and extending in a northwesterly direction for a number of miles is a series of highly faulted sedimentary beds lying on the granite to the west and having a general northeasterly dip. By reason of their attitude and the differences in the color of their outcrops, they present a banded appearance in the photograph. The cross faults are distinctly indicated by the displacement of the bands. The indistinctness of the outcrop in some places is due partly to vegetation and partly to soil creep.

Another very marked feature in both topography and vegetation is the line of contact still farther west between the granite-syenite series and the Quaternary gravels and sandstones that lie against it to the southwest. The fault block at C-1-2 is also prominently outlined in the topography. The older sedimentary series appears here as a featureless area supporting practically no vegetation as contrasted with the granite, which supports a sparse crop of stunted trees and bushes. In places the outcrops of bare granite may be distinctly seen.

The eastern portion of the area lying north of Silver City consists principally of Colorado shale (Cretaceous) which is not readily distinguishable from other formations in the aerial photograph. In the northeasterly corner there is a dome of Fierro limestone (Carboniferous) surrounded by a narrow belt of Beartooth quartzite (Cretaceous), which dips under the Colorado shale. Some of the light-colored bands in the quartzite may be traced in the photograph.

The geologic map accompanying this plate was taken from U. S. Geol. Survey Folio 199. The geology is described by Sidney Paige.[3]

Legend

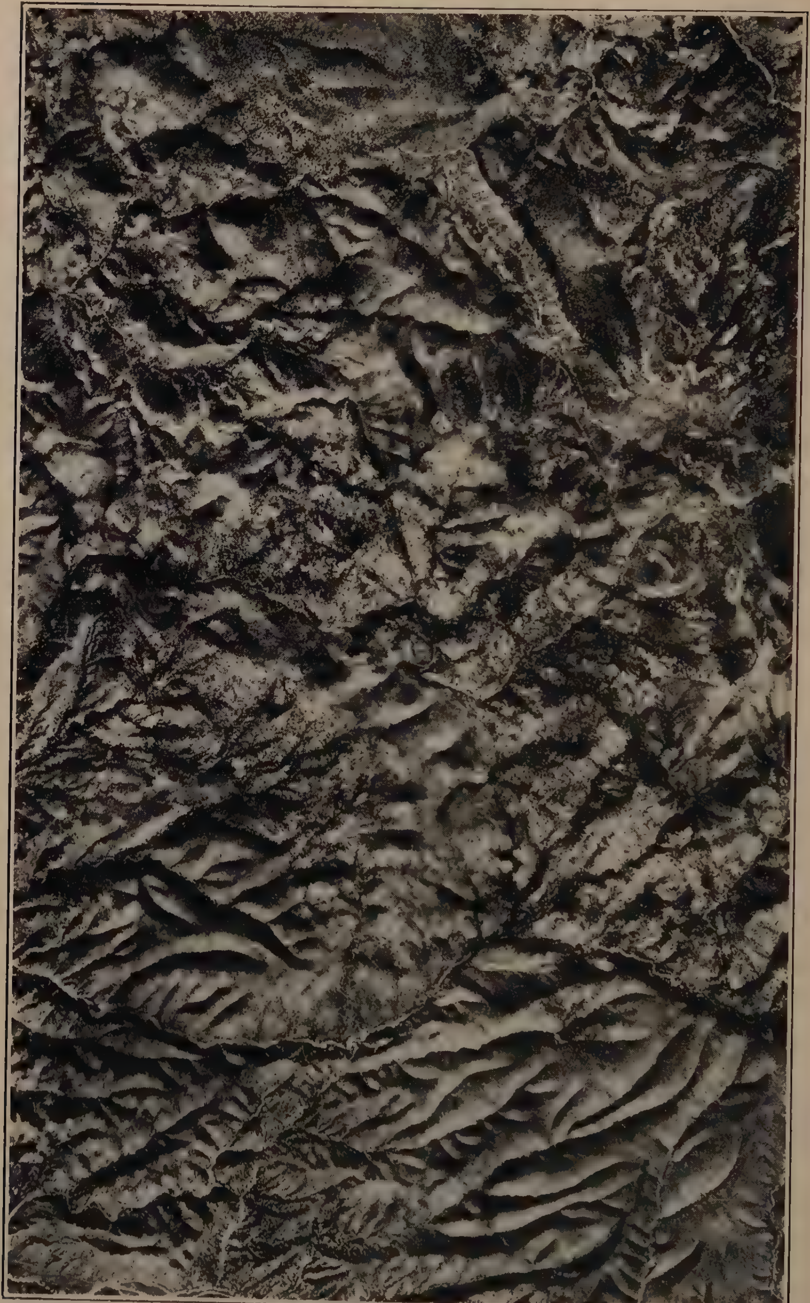
Sedimentary Rocks

Quaternary (Pleistocene and Recent)	*Qgs*	Gravel and sand	Including semiconsolidated sandstone and conglomerate
Tertiary	*Tgt*	Gravel, sand, and tuff	Partially consolidated and interbedded with Tertiary lavas
(Unconformity)			
Cretaceous (Upper Cretaceous)	*Kc*	Colorado shale	Shale, thin sandstone, and calcareous shale; some beds of Montana age may be included
	Kb	Beartooth quartzite	Quartzite with thin beds of shale locally

(Unconformity)			
Carboniferous (Pennsylvanian and Mississippian)	*Cf*	Fierro limestone	Gray, blue and black limestone with many cherty layers
	Cfm	Contact-metamorphosed Fierro limestone	Altered by igneous intrusion at Santa Rita and Hanover
Devonian (Upper Devonian)	*Dp*	Percha shale	Green to black shale
(Unconformity)			
Silurian-Ordovician	*SOfm*	Fusselman and Montoya limestones	Gray and pink limestone with many cherty layers; Fusselman, Silurian in age; Montoya, Upper Ordovician in age
Ordovician	*Oep*	El Paso limestone	Gray limestone with many cherty layers; a few beds that contain a Richmond fauna and belong to Montoya limestone included at the top in mapping
(Unconformity)			
Cambrian (Upper Cambrian)	*Ꞓb*	Bliss sandstone	Quartzite sandstone, calcareous sandstone, and glauconitic sandstone

IGNEOUS ROCKS

Quaternary	*Qb*	Basalt	Flows, with interbedded grave and sand
Tertiary	*Tir*	Intrusive rhyolite and quartz latite	Stocks and dikes
	Trl	Rhyolite and latite	Lava flows
	Tan	Andesite and basalt	Lava flows
Probably Late Cretaceous	*Kup*	Undifferentiated porphyries	
	Kgp	Granodiorite, quartz monzonite, and allied porphyries	
	Kgd	Granodiorite and more basic rocks at Pinos Altos	
	Kdp	Quartz-diorite porphyry	
	Kab	Andesitic breccia, andesite, and diorite porphyry	
Pré-Cambrian	*grs*	Granite, syenite, and allied porphyries	Includes fragments of schist



Courtesy Fairchild Aerial Surveys, Los Angeles, Calif.

FIG. 3.—SILVER CITY AREA, NEW MEXICO.

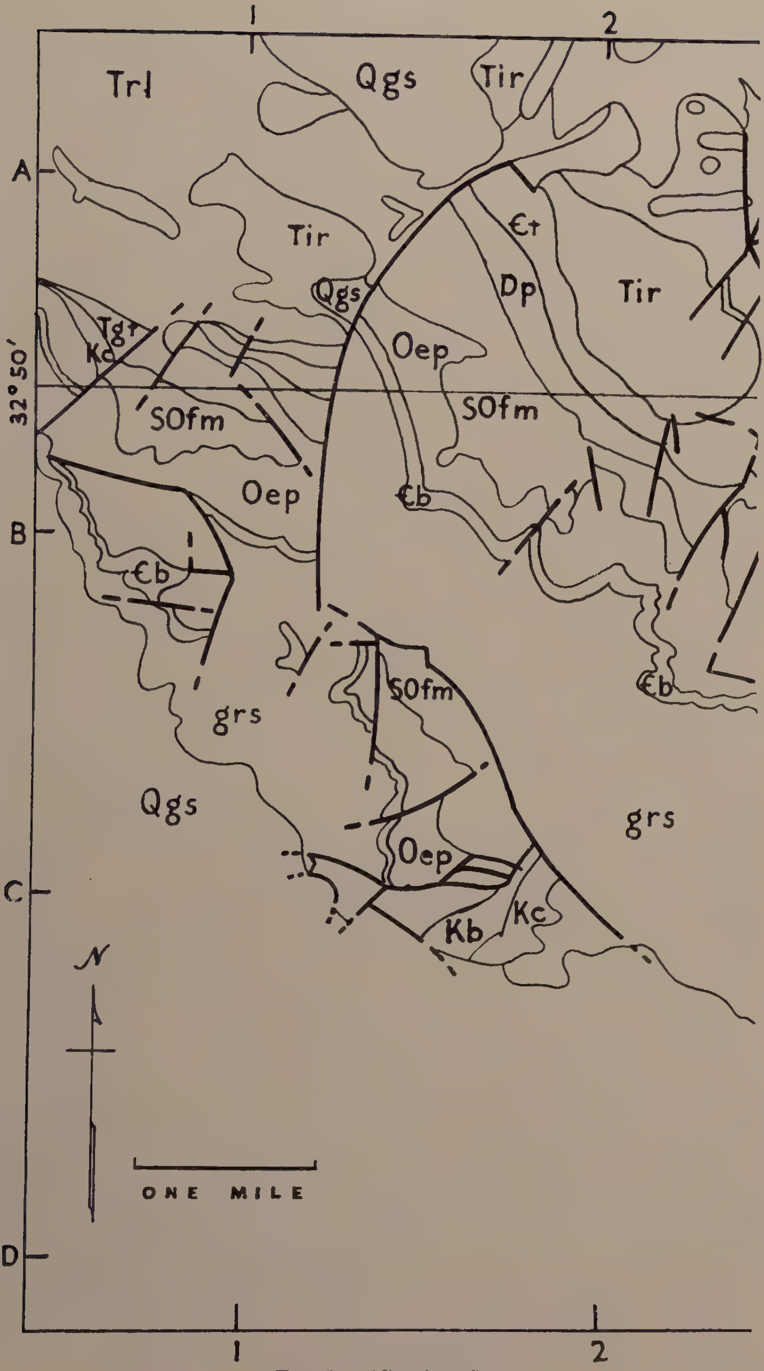


Fig. 3.—(*Continued*)

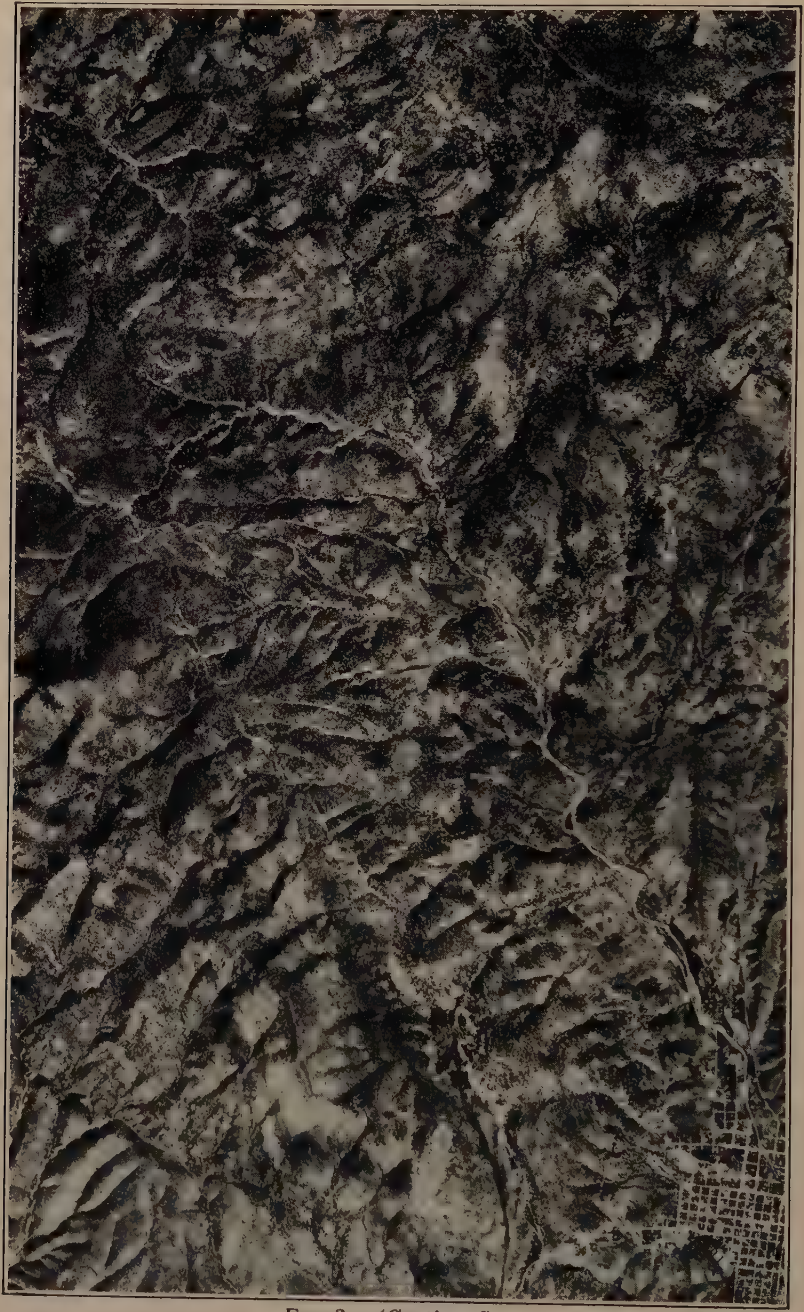


FIG. 3.—(*Continued*)

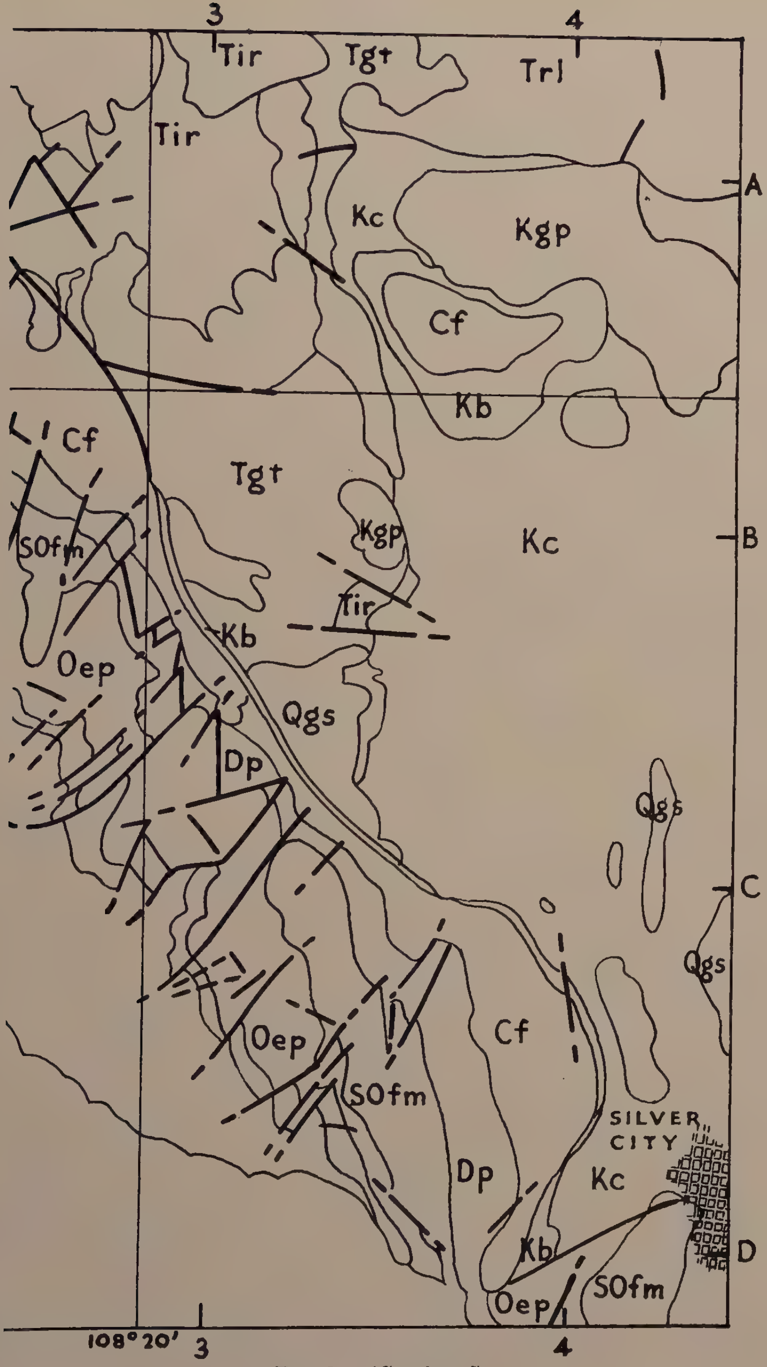


Fig. 3.—(*Continued*)

FIG. 4.—MOTHER LODE AREA

The area embraced by this plate lies in the Mother Lode district west of Sonora, in the foothills of the Sierra Nevada Mountains, California. This aerial photographic map shows what may be seen in the average moderately well watered areas in the western United States. Vegetation in areas such as this can frequently be used as a guide to the underlying rock formations, although the greatly reduced scale of the mosaic as reproduced does not bring this point out as clearly as might be desired.

The principal feature of interest is the fossil river extending nearly across the map from D-1 to B-3. This river bears a striking resemblance in the photograph to the present Stanislaus River, which lies to the west.

The lava that flowed down the canyon of the Tertiary river now forms the top of Table Mountain. The prominence of the old river channel in the photograph is due to the lack of vegetation on the lava sheet. The stream gravels underlying such Tertiary lava flows in this region furnished much of the placer gold mined in California in the early days. Sonora, one of the most famous of the early mining towns, is shown in the southeast corner of the photograph. The course of the series of veins forming the Mother Lode is indicated on the geologic map, which is taken from U. S. Geol. Survey *Prof. Paper* 157. The geology is described by Adolph Knopf.[4]

LEGEND

SURFICIAL ROCKS

Quaternary	*Pal*	Alluvium	Bordering streams and filling small valleys
	Pgv	River gravel	Usually auriferous

SEDIMENTARY ROCKS

Tertiary	*Ng*	Auriferous river gravel	
Jurassic (Upper Jurassic)	*Jm*	Mariposa formation	Slate, sandstone and conglomerate
Jurassic (?)	*ch*	Cherty beds	Banded green and chocolate sediments closely associated with the meta-andesitic tuffs
Carboniferous (Mississippian)	*Cc*	Calaveras formation	Slaty mica schists, chiefly biotite schist, quartzite, conglomerate, slate, chert, and limestone
	ls	Limestone	Lenses and irregular masses within the Calaveras formation

IGNEOUS ROCKS

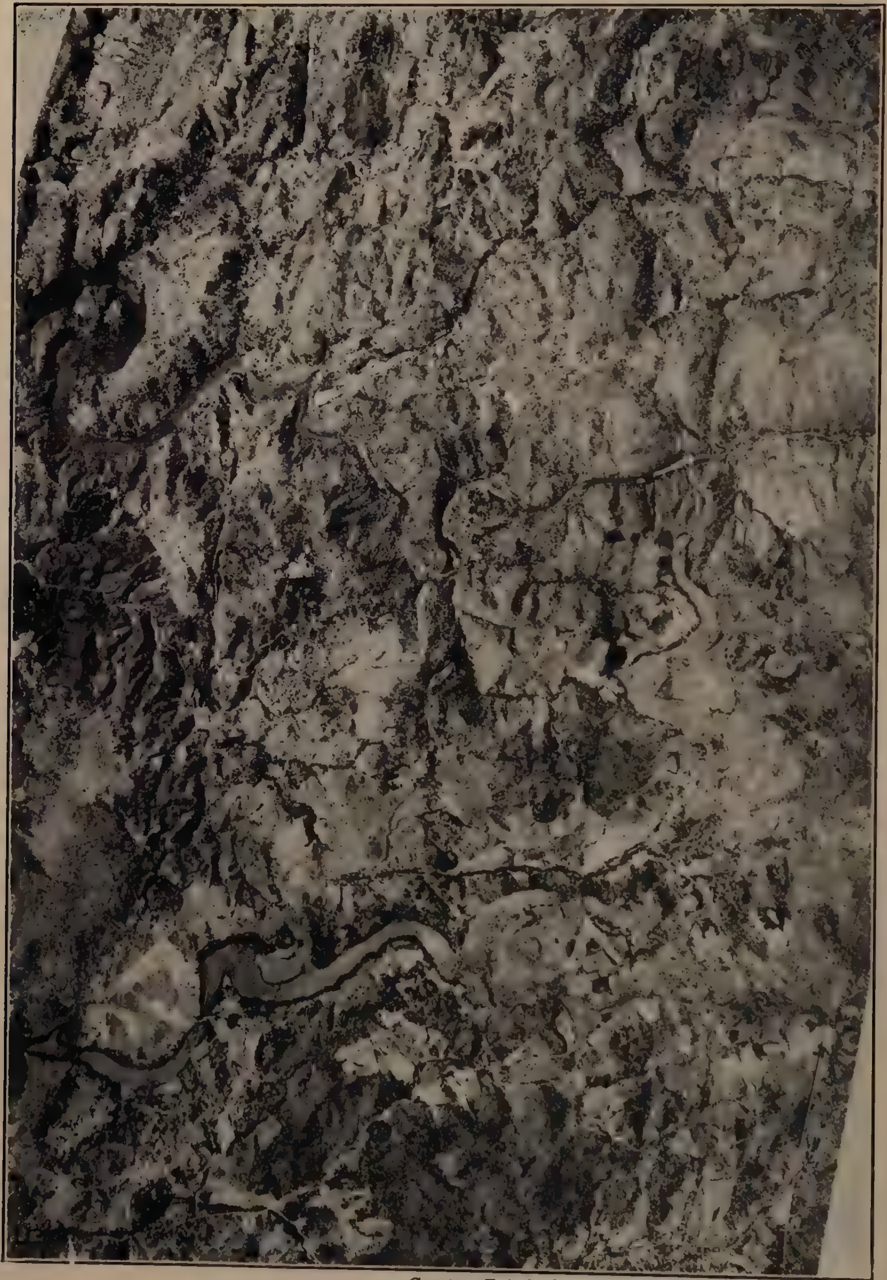
Tertiary	*Nl*	Latite	Rock intermediate between andesite and trachyte; lava flows
	Na	Andesite	Thick lava flows

	Nat	Andesite tuff, breccia, and conglomerate	Roughly stratified
	Nrt	Rhyolite tuff	Sometimes interstratified with gravel
Probably chiefly Late Jurassic or Early Cretaceous	*sy*	Soda syenite granophyre and related syenitic rocks	Dikes
	mdi	Metadiorite	Altered diorite, largely quartz diorite
	qdi	Quartz diorite	Batholithic intrusive masses
	grd	Granodiorite	Batholithic intrusive masses
	gb	Gabbro	Intrusive masses and dikes, usually associated with serpentine
	sp	Serpentine	Derived from periodotite and related basic intrusive rocks
Carboniferous, Triassic (?) and Jurassic	*mdb*	Metadiabase	Altered intrusive diabase and lava flows
	ma	Meta-andesite	Altered andesitic breccias, tuffs, and massive lavas, with some altered, basalt and diabase
	mha	Meta-hornblende andesite	Altered hornblende andesite breccia and tuff
	am	Amphibolite	Derived from basalt, andesite, and other igneous rocks
	ams	Amphibolite schist	Derived from andesitic tuff and breccia, diorite, and other igneous rocks
	ats	Amphibolite talc schist	
	qms	Quartz-muscovite schist	

FIG. 5.—SHIP ROCK AREA, NEW MEXICO

This area lies about 30 miles west of Farmington, N. M., and has been selected to illustrate the prominence with which dikes and other intrusive masses sometimes may be observed from the air. The Ship Rock is a famous landmark in this region and is one of the finest examples of dike intrusions in America. The dike material, monchiquite, has been intruded into Mancos shale (Cretaceous). The hard reefs of Dakota sandstone to the west are readily traceable in the photograph. This semiarid type of country is ideally adapted to the delineation of geologic features from the air.

Mention is made of Ship Rock on page 100 of *Professional Paper* 93. The geology of the region is described by Herbert E. Gregory.[5]



Courtesy Fairchild Aerial Surveys, Los Angeles, Calif.

FIG. 4.—MOTHER LODE AREA, NEAR SONORA, CALIFORNIA.

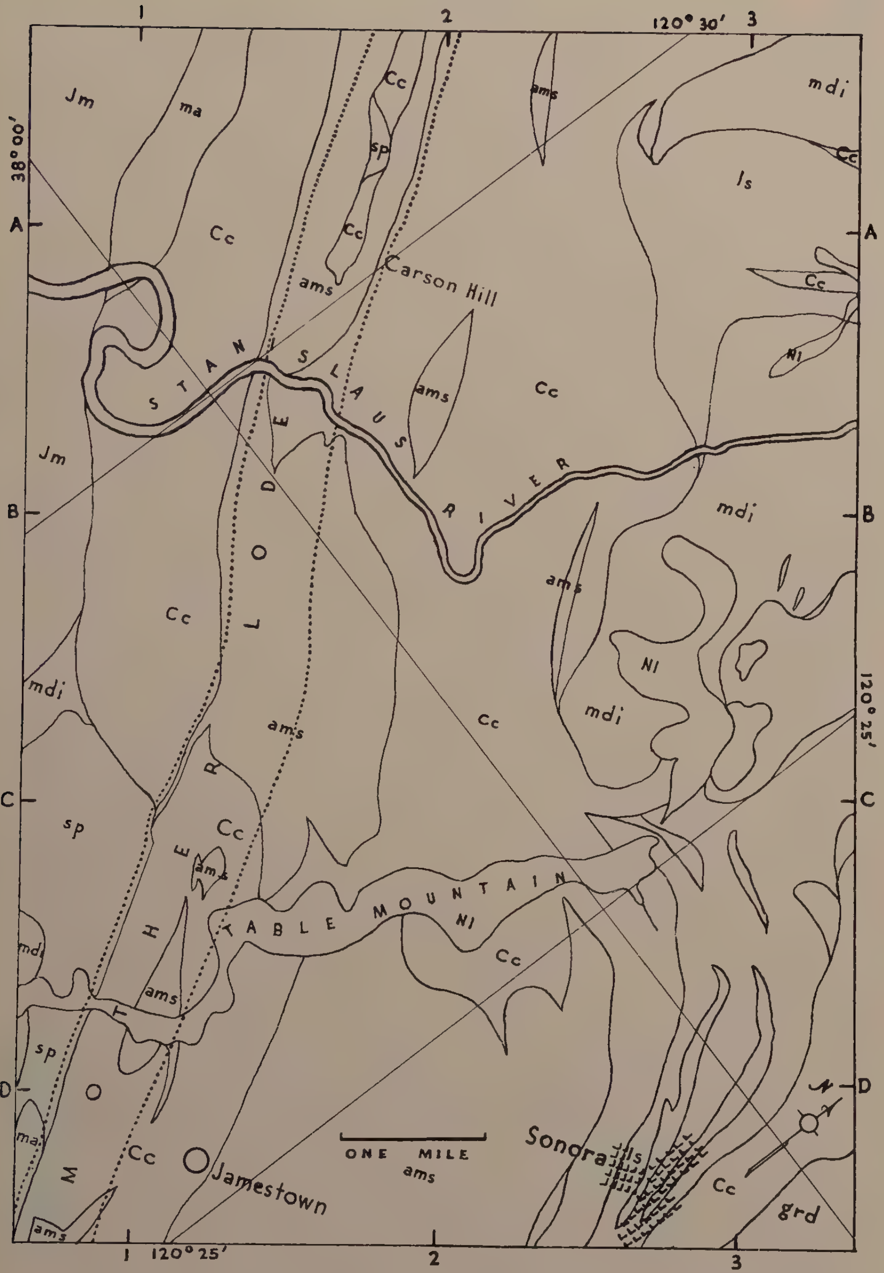
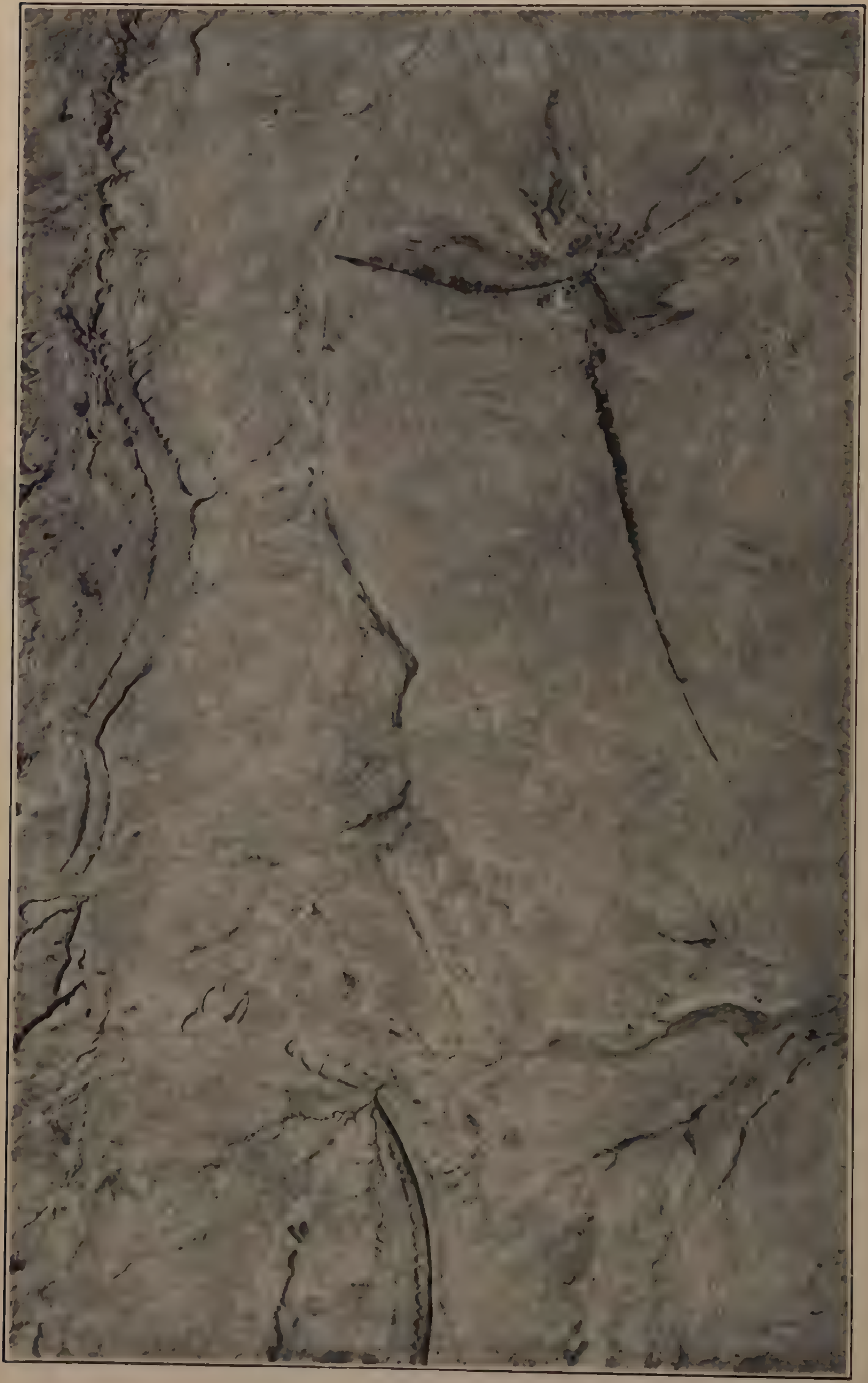


Fig. 4.—(*Continued*)



Courtesy Fairchild Aerial Surveys, Los Angeles, Calif.

FIG. 5.—SHIP ROCK AREA, NEW MEXICO.

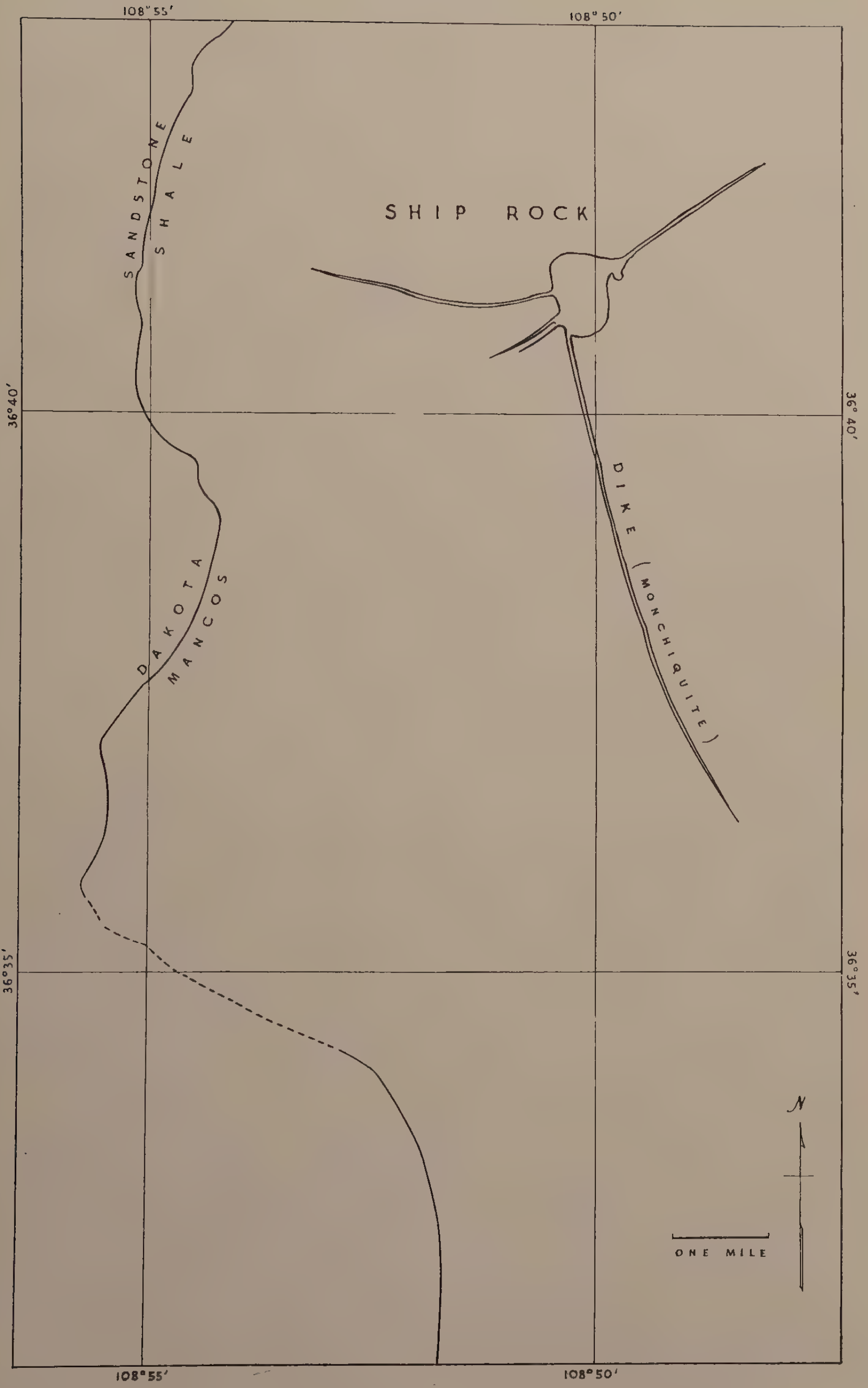


FIG. 5.—*(Continued)*

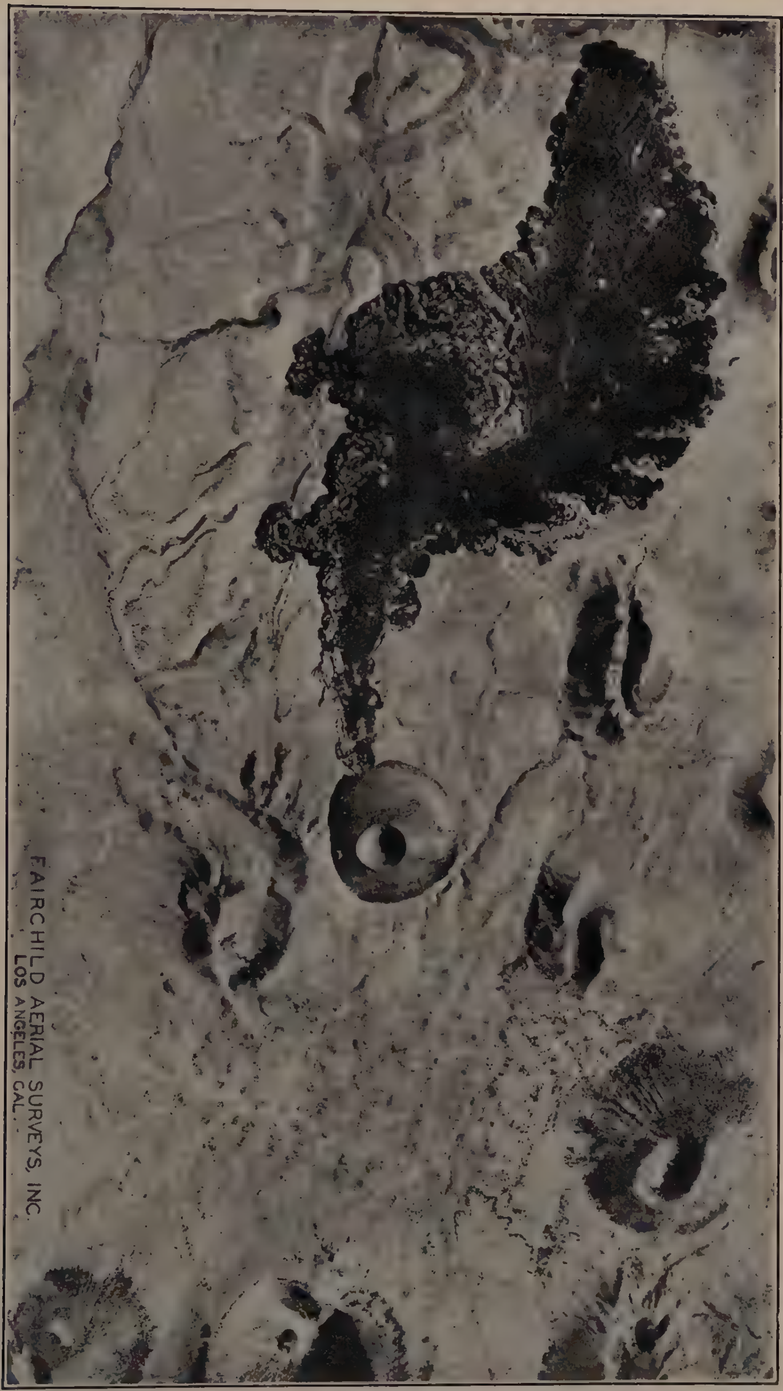
Fig. 6.—San Francisco Volcanic Area

The area embraced in this photograph lies about 30 miles north of Flagstaff, Ariz., and is a part of what is known as the San Francisco volcanic field, which covers a great area wherein are found many interesting phases of volcanism, all of which stand out even more prominently in the aerial photographs than on the ground. The volcanic field has been described by H. H. Robbins.[6]

The principal volcano in the photograph is perhaps the finest example of its kind in America. The time of the eruption is considered to be Quaternary, but all of the activity was not simultaneous, as is evidenced by the varying degrees of erosion in the different cones.

The country rock through which the eruptions have taken place is Kaibab limestone. The outflow of basaltic lava and the subsequent cinder cone of the main volcano are perfect and almost untouched by erosion, while the two cones lying to the east appear to be split in a north-south direction and eroded in such a manner as to suggest recent faulting, probably along the same fault line through which the cones were originally extruded.

The quaternary volcano has been described by Douglas W. Johnson [7]



Courtesy Fairchild Aerial Surveys, Los Angeles, Calif.

Fig. 6.—San Francisco Volcanic Area, near Flagstaff, Arizona.

Fig. 7.—Coal-bearing Area

The area included in this photograph lies 8 miles northeast of the town of Gallup, N. M., and is typical of the coal-bearing rocks of this part of the country. The geologic formations involved are all Upper Cretaceous. The coal measures are in the base of the Mesa Verde formation and are known locally as the Dilco and Gallup sandstone coal members. The coal beds in this area are thin (averaging from 2 to 3 ft.), are very lenticular, and in many instances are not readily traceable from one locality to another.

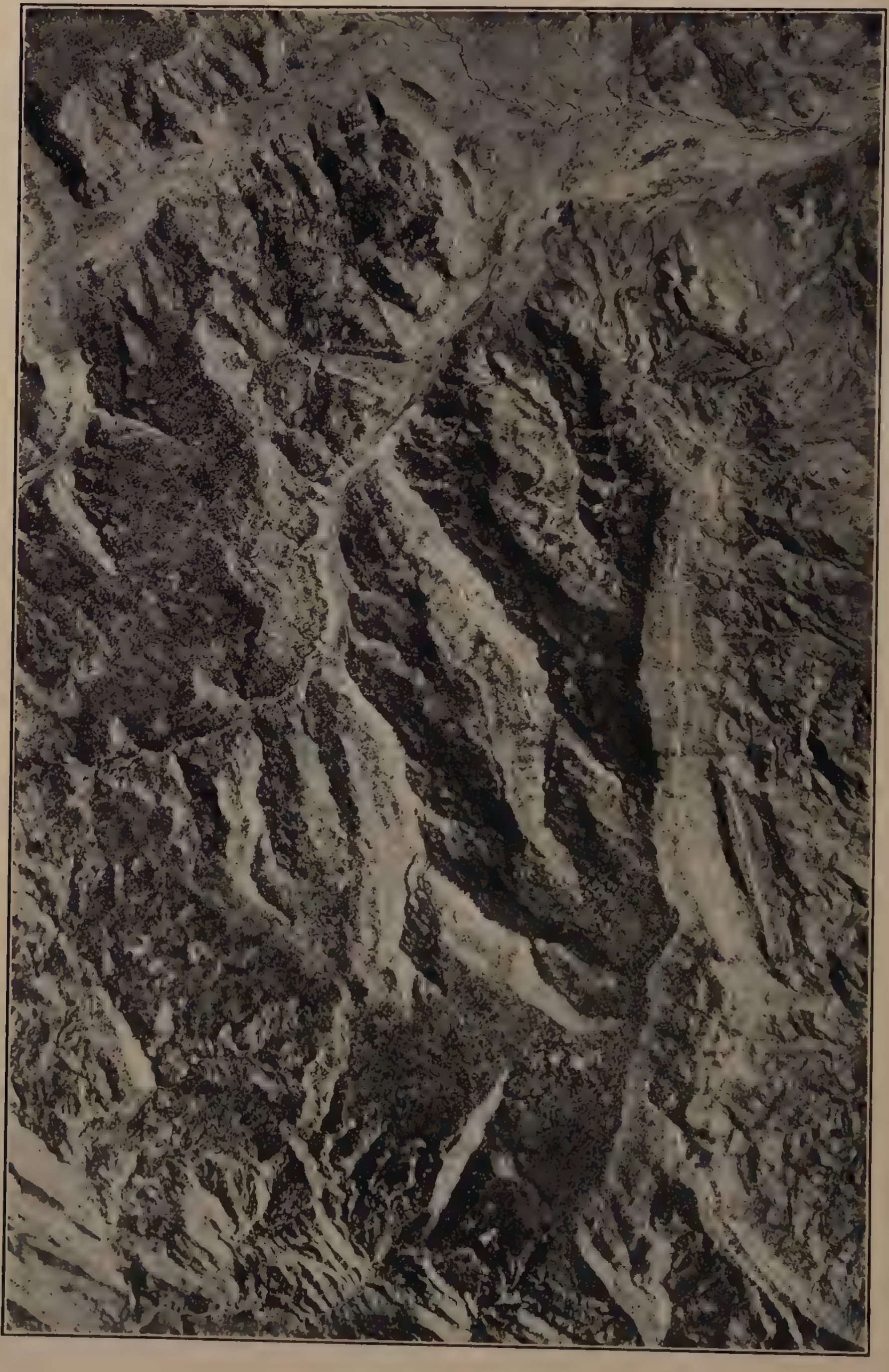
The coal outcrops do not show readily in a photograph but the light colored interbedded sandstones are extremely prominent and may be easily traced in aerial photographs, thus greatly simplifying the work of the field geologist. The lenticularity of the bedding in this region may be seen beautifully in the escarpments where the bedding is not obscured by soil or vegetation.

The geologic map is taken from U. S. Geol. Survey *Bull.* 860-A. The geology of the area is described by Julian D. Sears.[8]

Legend

Cretaceous	*Kbb*	Mesaverde formation	Bartlett barren member (alternating sandstone and clay with a little coal)
	Kds		Dalton sandstone member (massive and thick-bedded sandstones)
	Kdc		Dilco coal member (alternating sandstone and clay with important beds of coal)
	Kgs		Gallup sandstone member (massive sandstone clay and shale with some thick lenses of coal)
	Km	Mancos formation	Chiefly gray marine shale

Note: The principal coal beds are indicated by dotted lines.



Courtesy Fairchild Aerial Surveys, Los Angeles, Calif.

FIG. 7.—COAL-BEARING AREA, NEAR GALLUP, NEW MEXICO.

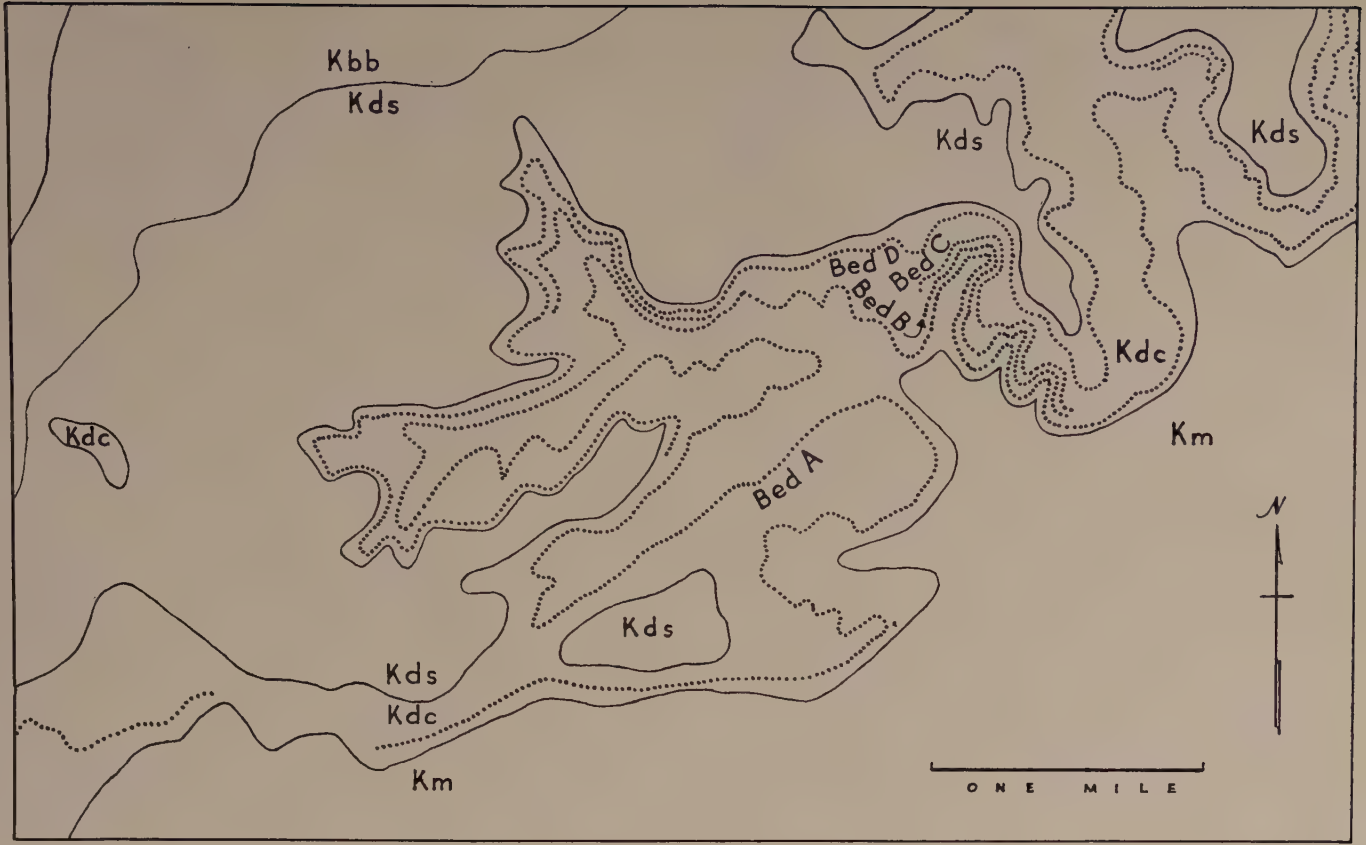
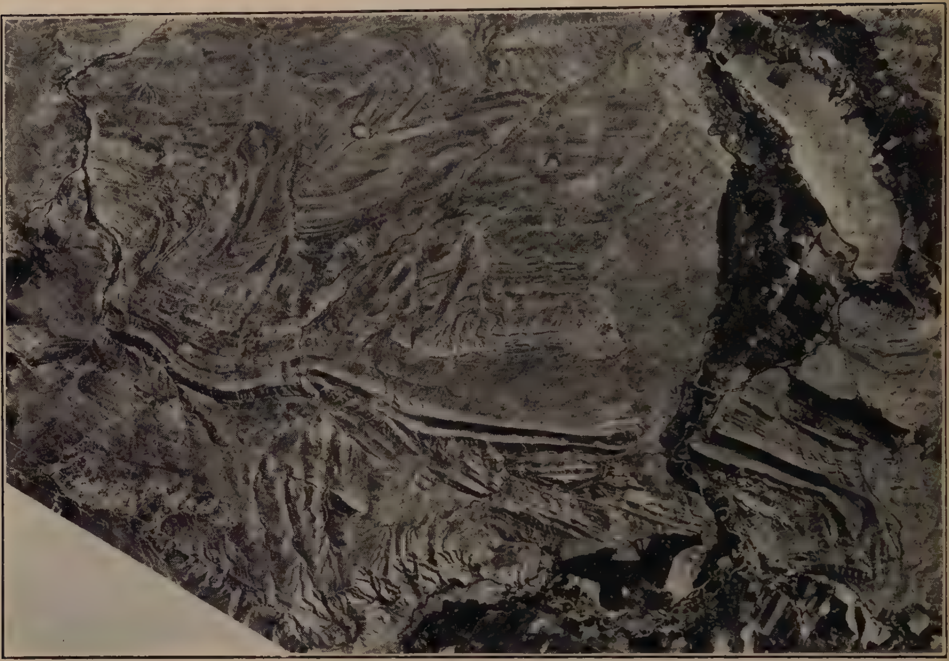


Fig. 7.—(*Continued*)



Courtesy Fairchild Aerial Surveys, Los Angeles, Calif.

FIG. 8.—OIL-FIELD AREA, NEAR LANDER, WYOMING. (CONTINUED ON PAGES 397–399.)

FIG. 8.—OIL-FIELD AREA

The area shown in this map lies easterly from the town of Lander, Wyo., and was chosen as illustrative of the maximum that may be shown in aerial photographs in the way of stratigraphic and structural conditions. The terrain is one of moderate relief and very sparse vegetation. The inclination of the strata is high, in most instances being above 25°. There are few regions in which all of the minute details of geologic structure and bedding will show in an aerial photograph as they do here.

The geology is almost as readily traceable on the surface as it is from the air, with the possible exception of the northeastern portion of the area wherein the structure is quite visible in the aerial photograph but, owing to the low relief and consequent soil cover, the fairly complex folding might escape the attention of a geologist working on the ground without the aid of the aerial map. It will be noted in the accompanying geologic map by Woodruff[9] that the subsurface contouring is carried directly across the folds of the structure as shown in the aerial photograph.

The closing beds, encircling the various domes along the uplift may be easily traced and minor faults appear sharply defined. An aerial map such as this completely eliminates the need of a laborious and time-consuming plane-table survey.

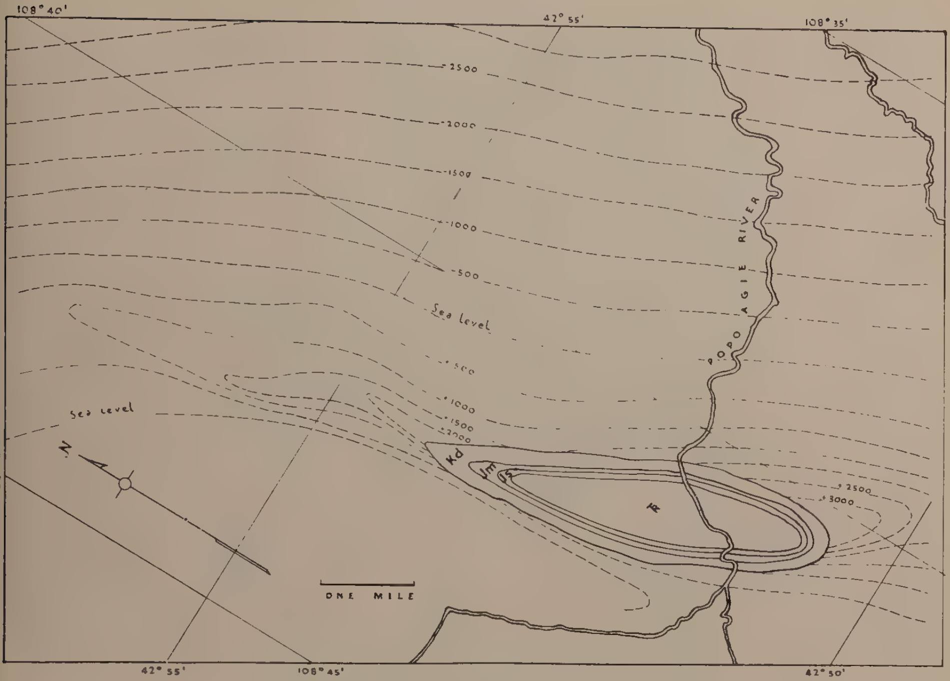


FIG. 8.—(*Continued*)

It should be stated that the photographic map herewith reproduced was compiled without any intent of great accuracy but it was found that the geologic map coincided almost exactly.

LEGEND

Tertiary	*Twr*	Wind River formation	Sandy shale, shaly sandstone, and conglomerate
Cretaceous-Jurassic	*Kmv*	Mesaverde formation	Massive light buff sandstone and sandy shale; coal-bearing
	Kms	Mancos shale	Drab sandy shale with some sandstones
	Kd	Dakota sandstone and Lower Cretaceous	Massive ferruginous sandstone and sandy shale
	Jm	Morrison formation	Maroon sandy shale and conglomerate
	Js	Sundance formation	Olive-green fossiliferous limestone and shale
Triassic (?)	*Tr*	Chugwater formation	Red shale and massive red sandstones

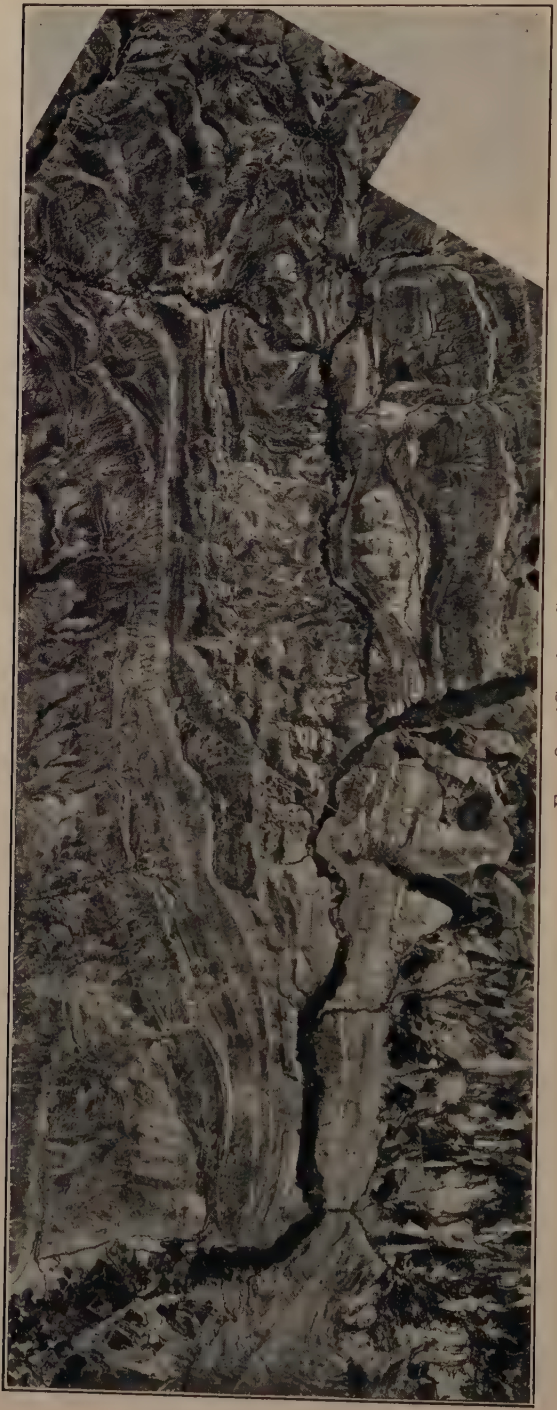


FIG. 8.—(*Continued*)

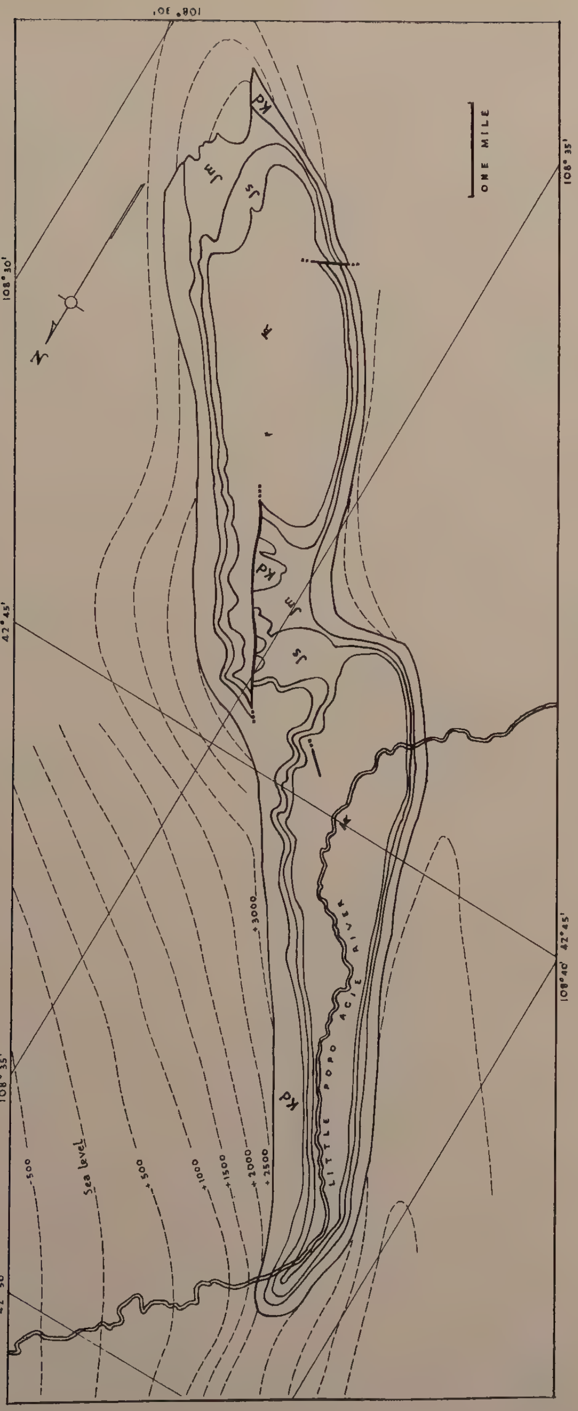


FIG. 8.—(*Continued*)

FIG. 9.—BUTTONWILLOW GAS FIELD

The Buttonwillow gas field lies east of the town of Taft, near the southern end of the San Joaquin Valley, Calif., and represents an excellent example of the distinctness with which oil and gas structures may sometimes be observed from the air in regions of such low relief as to appear almost a level plane when viewed from the surface of the ground. The accompanying contour map indicates that the north and south domes are slightly elevated above the general plane of the valley floor, thus forming two areas that have become islands in times of flood. In this way, more or less sandy shorelines have been formed, appearing as white margins outlining the domes and contrasting markedly with the dark alkali soil, which predominates in this part of the valley. There is no surface evidence of structure in this area beyond the slight topographic rise. The flat-lying Quaternary lake beds that cover the surface are of considerable thickness and lie unconformably on the gas-bearing formations beneath.

Wells have been drilled in both the north and south domes, but so far production has been found only in the north dome.

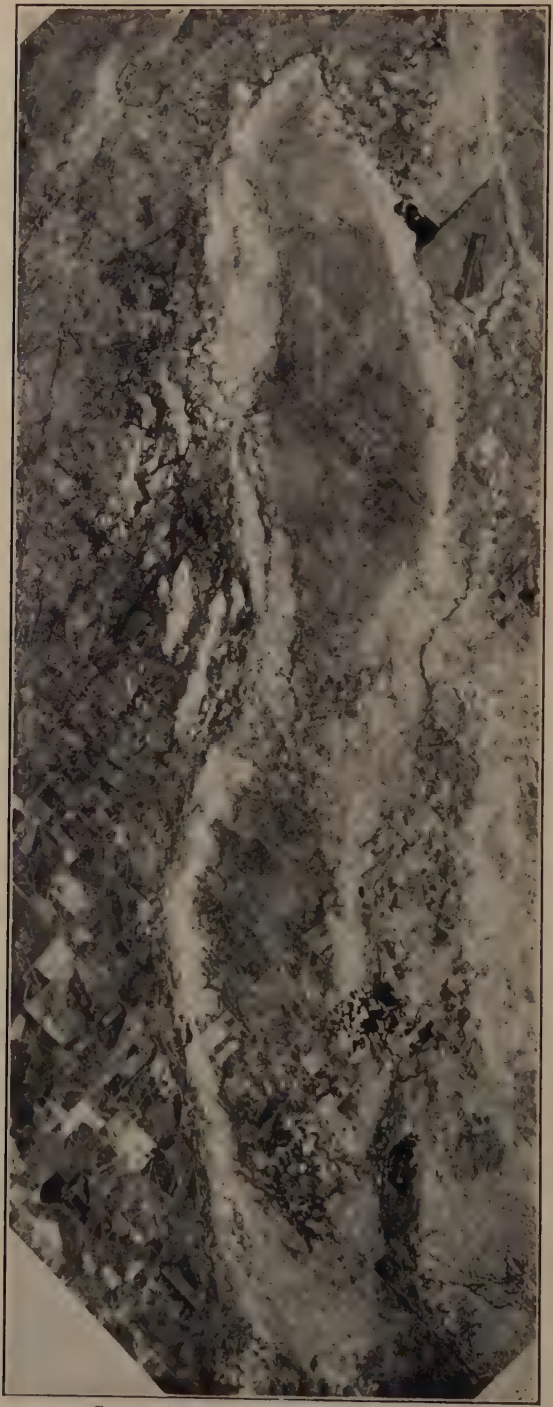
In the photograph a number of white dots run just south of the center of the north dome. These represent shot points in a geophysical survey that was conducted subsequent to the development of the field.

This field was not discovered directly by means of aerial photography, but its striking appearance from the air led to a detailed topographic survey, which outlined the structure and resulted in the drilling of the discovery well. The field has been described by E. H. Musser.[10]

FIG. 10.—AREA EAST OF MT. POSO OIL FIELD

This area lies about 18 miles northeast of the town of Bakersfield, Calif. and 4 miles east of the Mt. Poso field. It has been chosen as showing remarkably well the difference in appearance between areas of granite as compared to those of sedimentary rocks where the topography is similar in both cases. The contact between the Tertiary sediments in the western part of the area and the granite mass to the east can be clearly seen in the photograph and may be readily followed for many miles from an airplane.

The sedimentary rocks are chalky shales, very light in color and lying almost flat. In the granite area the bare rock protrudes at frequent intervals through the sparse soil covering.



Courtesy Fairchild Aerial Surveys, Los Angeles, Calif.

FIG. 9. BUTTONWILLOW GAS FIELD, NEAR TAFT, CALIFORNIA.

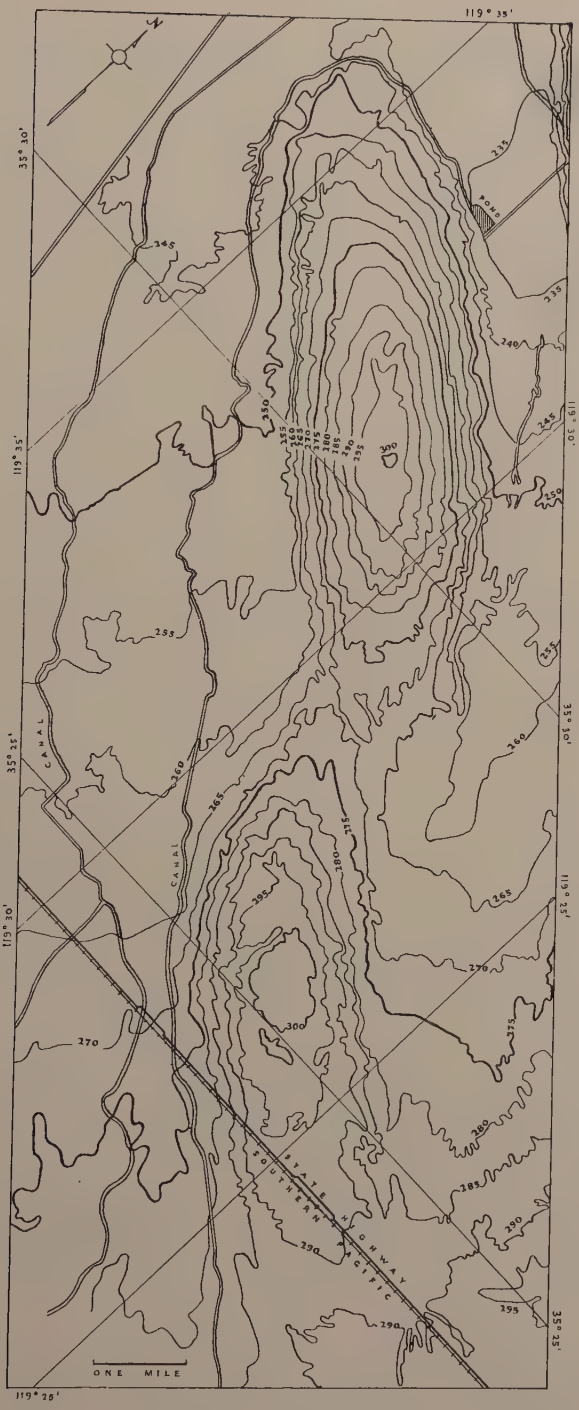
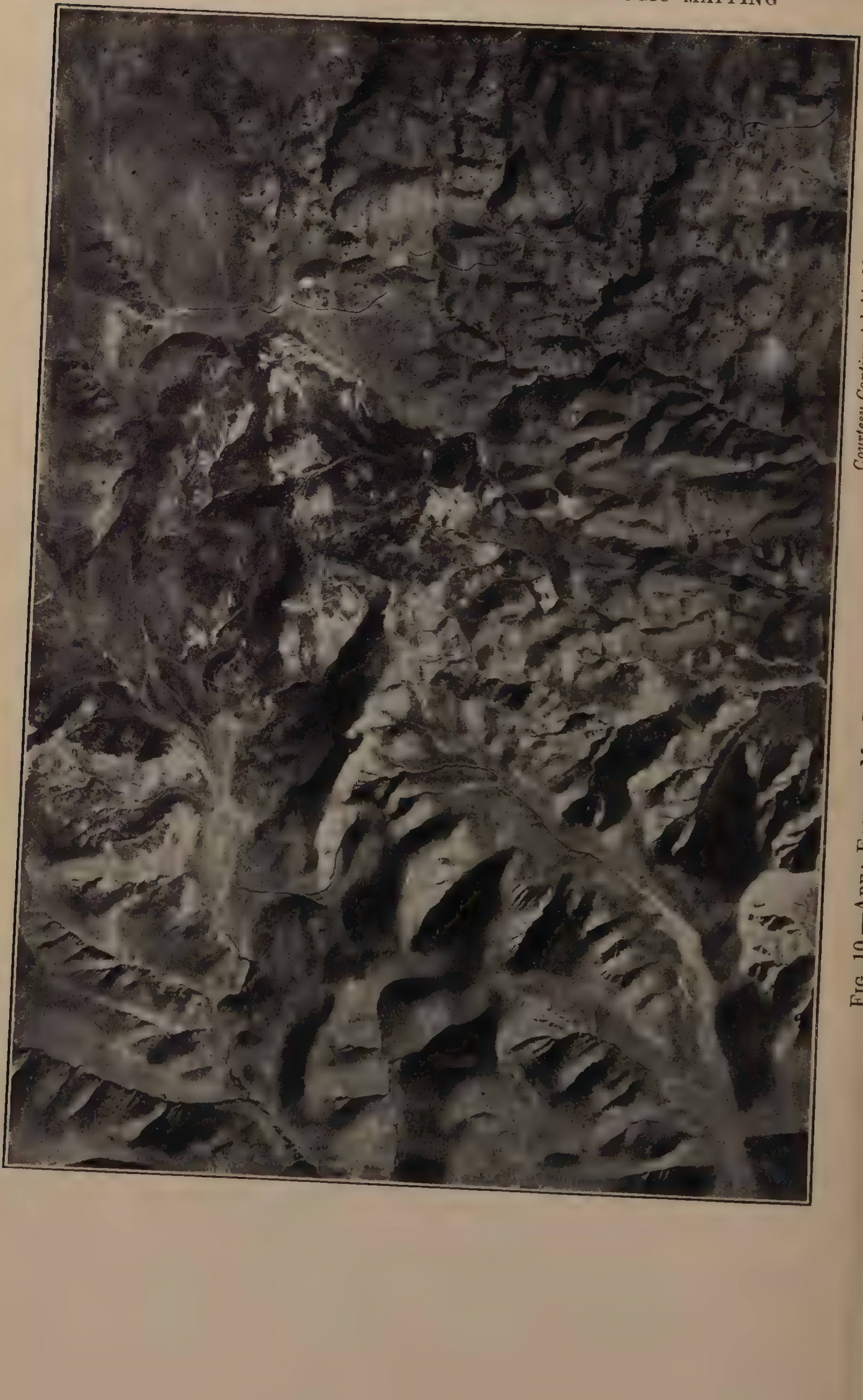


FIG. 9.—(*Continued*)



Courtesy Continental Air Map Co., Los Angeles, Calif.

Fig. 10.—Area East of Mt. Poso Oil Field, near Bakersfield, California

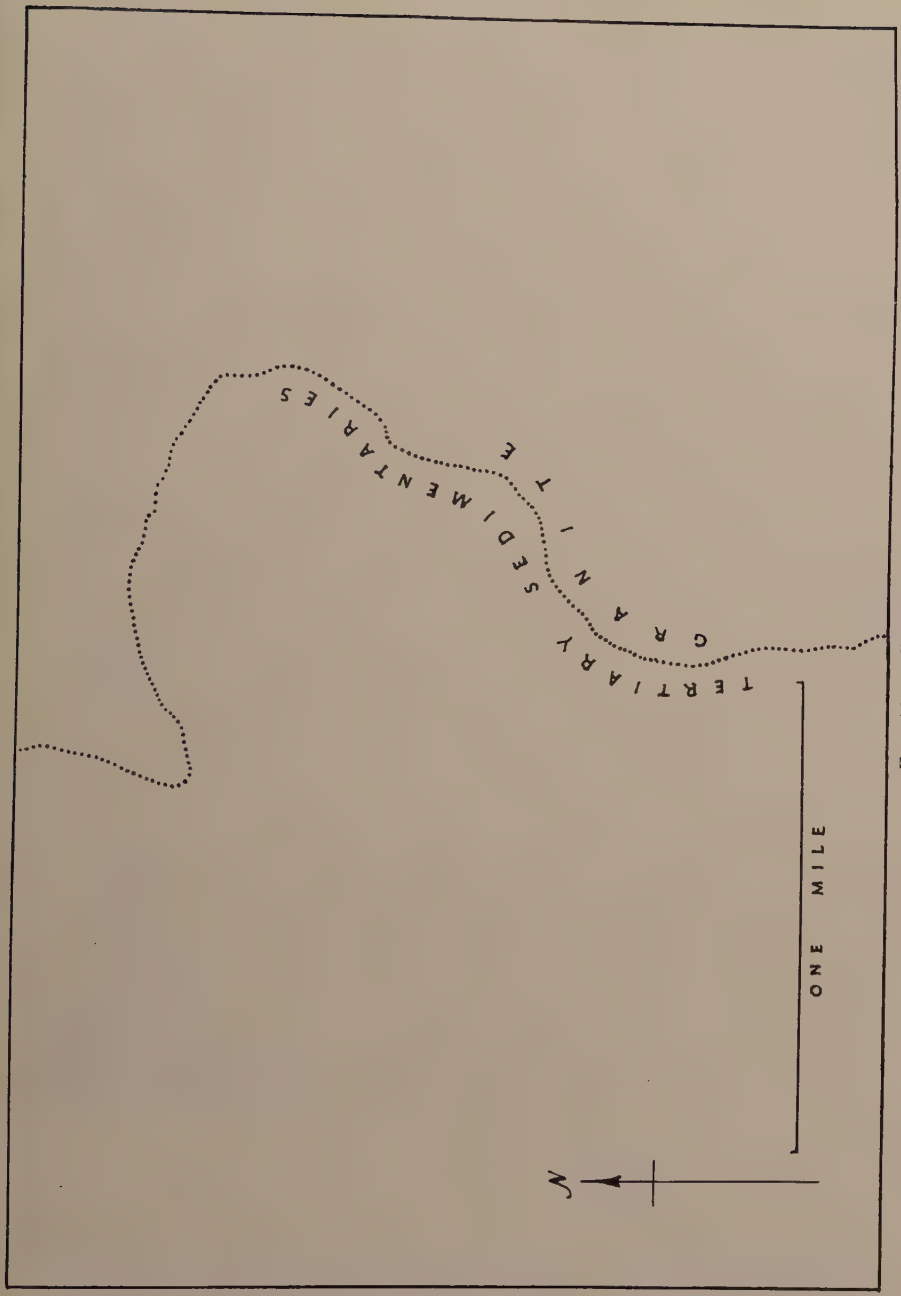
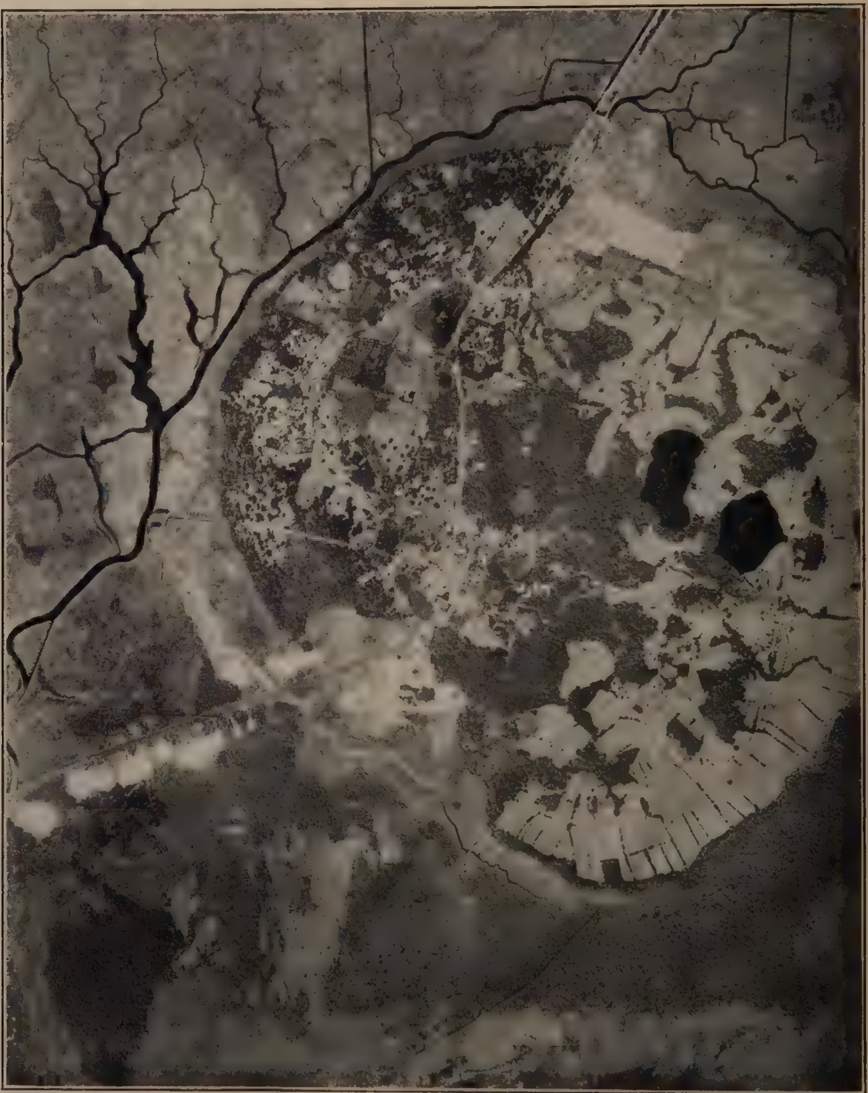


Fig. 10.—(*Continued*)

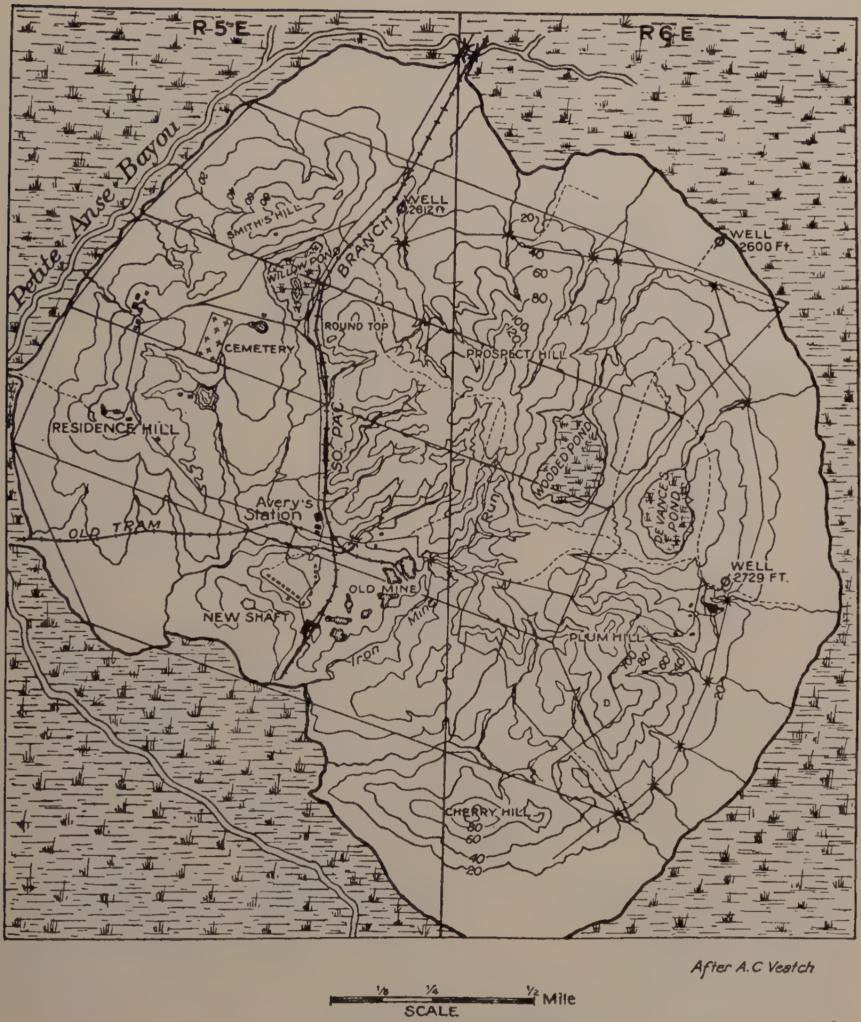


Courtesy Edgar Tobin Aerial Surveys, San Antonio, Tex.

FIG. 11.—AVERY ISLAND, NEAR NEW IBERIA, LOUISIANA.

Avery Island is about 10 miles southwest of New Iberia, La., in the marsh lands bordering on the Gulf of Mexico. This island is the second of a series of five elevations extending in a southeasterly line to the mouth of Atchafalaya River. The islands are the surface evidence of salt domes. These domes produce the finest quality of salt known in this country, but none to date have been productive of oil in commercial quantities.

Avery Island has a long and interesting history behind it, its saline springs having been used by prehistoric races as a source of salt. Abun-



After A.C Veatch

Courtesy Amer. Assn. Petr. Geol.

FIG. 11.—(*Continued*)

dant fossils, both vertebrate and invertebrate, indicate the date of the uplift to be post-Pleistocene.

The outline of the salt dome is distinctly delineated by the vegetation, which has been partly removed by cultivation but still indicates the shore line by the marked difference in size and density of trees on the island, as compared to the stunted or total lack of trees in the swamp area. Salt domes in general may be observed from the air, even when not in swamp areas.

The islands have been described by numerous writers, the most recent article being that of F. E. Vaughan.[11]

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10. E. H. Musser: The Buttonwillow Gas Field. *California Oil Fields* (1930) **15**, No. 3.
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DISCUSSION

(*W. E. D. Stokes, Jr., presiding*)

V. A. Wynne, Albany, N. Y.—In connection with the use of airplane photographs in field work, I wonder if it is generally understood that a stereoscope is not necessary in order to bring out the relief. If the adjacent views of a strip of land are brought in proximity, it will be found, after a little practice, that in viewing them they will quite suddenly blend together and show up the relief of the land features in surprising clarity. In the photographs shown by Mr. Loel, the hills and depressions are well delineated by the lights and shades, but in wooded land of low rolling topography it is often difficult to tell the form of the surface without utilizing the stereoscope principle and duplicate views. Likewise, by this means the location of one's position in such terrain is greatly facilitated, as is the accurate placing of determined elevations at changes in slope of the ground, and the drawing of contour lines in the field as well, when desired.

To avoid undue eyestrain the distance between corresponding points on the two adjacent views should not greatly exceed eye-spacing. Utilizing 7 by 9-in. prints, this requirement can be met without folding, except for the center strip of the overlap section.

For use by the geologist, it is suggested that only alternate photographs of a flight series be mounted on cloth. With the customary 60 per cent overlap, this still involves some trimming, and the visible displacement of points between prints will still not be serious, as it might be in so assembling a mosaic. This now leaves a set of every other alternate print in the series, which is left unmounted, and these prints are utilized in conjunction with the mounted set for the binocular aspect, by folding longitudinally when required to bring corresponding sections within operating range.

The foregoing observations are based on practical applications over an extended period, some 10 years ago.

W. Loel (author's reply).—The stereoscopic viewing of aerial photographs without mechanical aid is useful to those who are able to so train their eyes as to take advantage of the possibility. It has been found, however, that relatively few people are able to accomplish unaided stereoscopic vision, owing, probably, to somewhat unequal perceptive ability in the eyes. For those desiring to try this method reference is made to B. B. Talley's treatise on photogrammetry.[12]

There is a condition relative to the stereoscopic study of aerial photographs which does not seem to be widely known, and which may be useful to geologists. It is customary to place the prints in the stereoscope in the same relation to each other as that in which the photographs were taken. This position gives the maximum amount of stereoscopic effect. If the topography is more than moderately steep and the overlap between pictures is 60 per cent, the apparent accentuation will be so great as to be objectionable for many uses. The apparent relief may be reduced to any desired amount by revolving the two prints equal amounts in the same direction. If the right-hand print is rotated about its center, the left-hand print should be rotated about the image of the object found at the center of the right-hand print.

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[12] B. B. Talley: Engineering Applications of Aerial and Terrestrial Photogrammetry, 221–223. Pitman Pub. Corp. New York, Chicago, 1938.

New Method of Mapping with Aid of Aerial Photographs and Slotted Templets

By W. H. Meyer, Jr.*

(New York Meeting, February 1939)

Although an aerial photograph is not a map, most of the information that is necessary for compiling a map is recorded in the photograph provided some form of radial-line method is used to determine the true position of images. The slotted-templet method, which is based on the well-established radial-line principle, has made it possible to construct accurate mosaic maps at a cost comparable with that formerly charged for the average mosaic. It makes possible the securing of these results with far less ground control, which is always expensive. It has expanded widely the possible use of aerial photographs for mapping.

Although a vertical or oblique aerial photograph is not a map, most of the information that is necessary for compiling a map is recorded in the photograph. Some ground controls or data are needed, the number and accuracy to be governed by the mapping method to be used and the scale and final accuracy desired in the finished map.

Radial-line Control

It is essential that the principle of radial-line control in the use of vertical aerial photographs be understood and accepted before any confidence in the slotted-templet method can be gained. A simple sketch and some enlargements showing the Empire State Building will serve to illustrate the cause of displacement of an image that is above the datum plane as recorded in the photograph. The top of the tower of the Empire State Building is directly above the base, and when the image of the top is shown almost two blocks away from the center of the base, it is evident that the image of the top of the tower is not the true location, and in this particular case we know where the true location is; namely, over the center of the base of the tower. If the top of the tower were the top of a hill 1250 ft. high, we would have no way of knowing by inspection the true position of the top of the hill, so it is very important to have a method whereby the true location of any such point can be determined, and thereby make it possible to convert the detail of an aerial photograph into accurate information for mapmaking.

Manuscript received at the office of the Institute Jan. 13, 1939. Issued as T.P. 1081 in Mining Technology, July 1939.

* General Manager, Fairchild Aerial Surveys, Inc., New York, N. Y.

The method is based on the fact that the true position or shift of an image due to being on a different plane from that of the surrounding images is always along a line from the center of the print through the image point. It may be in toward the center or farther out along this so-called radial line than the recorded image. If we are very careful to pick the same image point on three or more overlapping prints that have their centers spaced along the line of flight, and will draw a line through it from the centers of the respective prints on which it is shown, we will soon discover that the radial lines intersect. This intersection will be the true position of the image. Its location may be solved mathematically; Prof. Earl Church, of Syracuse University, has done work along these lines. However, in most instances it is more readily solved graphically. At first it was accomplished by using long strips of tracing paper the width of the prints and as long as the line of flight. With 55 to 60 per cent overlap in line of flight, the image points of the centers of three successive prints always appear on each picture. Each print was slipped under the tracing paper, the center located and the print oriented so that the centers of the overlapping prints coincided. When radial lines are drawn on the tracing paper to the image points selected on three successive prints, we secure an intersection, which is the true location of the image.

This method was used for years as a means of locating the true position of image points shown in vertical aerial photographs. It took a great deal of time, was difficult to use where scale variations had to be compensated for on each picture, and it was difficult to detect errors in the work.

At a later date a modification of this method was devised wherein transparent sheets are used, one corresponding to each print, and a set of radial lines as well as the three centers are indicated on each; that is, on the sheet the center of the print is indicated and from this radial lines are drawn to previously selected points on the print, usually three, along each of the edges parallel to the line of flight. Also, to make it possible to orient the transparent sheets, the centers of the other two overlapping prints must be indicated. On each transparent sheet we now have the centers of three overlapping prints with six radial lines and are ready to lay these down on a large table. At least three overlapping transparent sheets will cover every part of the area. The intersection of the radial lines will show and the centers will coincide.

When one strip of transparent sheets has been laid and fastened together with scotch tape so as to be in proper alignment and fit the control for that strip, the adjacent strip is laid in a similar way, the selected radial-line image points of the second strip being identical to those selected on the first strip where the two strips overlap. This will give six radial lines intersecting to give the true location of the selected point if it shows on two overlapping strips. (The intersection of the lines is seldom perfect and considerable adjustment is required before a satisfactory layout of all the points can be secured. If the flight scale is not the same on all the strips, it will need to be adjusted to fit control and the scale of the overlapping strips.) After the layout has been adjusted to fit control and give the best possible intersections, the centers and the intersections are transferred to a large transparent sheet. It is from this sheet that the data are transferred to the board on which the mosaic prints are to be laid. It requires considerable time and patience to get a large number of sheets properly adjusted and fixed to stay in place until the large transparent sheets are traced off. The tape slips or loosens, and changes in temperature or humidity affect the transparent sheets.

Slotted Templet

The slotted-templet method is very similar to the aforementioned method, but the difficulties of adjusting and keeping the layout in place are eliminated by slots and posts, and the tracing of the layout for transfer to the mosaic board is avoided. No new principle is involved and the result obtained is based on the radial-line method, which has been proved by years of use whenever an accurate map has been made with the aid of aerial photographs. However, the facility with which the slotted-templet method may be used has materially widened the field and usefulness of the radial-line method. In the past only small areas, or those on which considerable time and money could be spent, were mapped by aerial photographs and the radial-line method, but the slotted-templet method can be used on all mosaic work or on reconnaissance line-drawn maps.

The slotted templets are more readily made than individual transparent sheets. After the points have been accurately selected on the prints so that at least nine points are used for each print, a card or templet is placed under the print and a needle point is used to penetrate through the selected points on the print into the templet. In doing this, care must be used to keep the needle point perpendicular to the print, so that the point will be marked on the templet directly beneath the point selected on the print. To facilitate the operation, it is advisable to have a soft base under the templet and immediately after pricking it to circle each hole with a pencil mark, so that the hole may be readily found for the next operation.

A templet has nine needle points: the center of the print used, the center of the previous overlapping print, the center of the next overlapping print in line of flight and six wing points, all of which are common to the overlapping prints and may also be common to neighboring or adjacent overlapping flight strips. The next operation is to punch a hole concentric with the point located as the center of the print of which the templet is being made. This hole is the size of the post in the cutting machine, as well as the posts used in assembling the templets. The cutting machine has been designed so that the slots cut in the templet will be accurately along the radial line from the center point through the other points marked on the templet. This is accomplished by having a post in the machine mounted in a block of metal, which is free to move in a groove forward or back and in line with a locating pin in the center of a die, which cuts out the slot. The templet having had the center hole punched out is placed over this post. The templet is free to move in or out from the cutting die and may also be revolved about the center post. By the aid of the locating pin, which protrudes through the center of the die, it is now possible to move the templet so that on beginning the cutting stroke the locating pin first strikes the templet exactly in the needle point previously marked. When this position has been reached, the stroke is completed; the pin recedes into the die and the die cuts out a slot 2 in. long and just $\frac{1}{1000}$ in. wider than the posts that are to be used in assembling the templets (approximate width of slot $\frac{1}{8}$ in.). All of this can be accomplished in much less time than it takes to explain it. Eight or more slots are cut in each templet in about 45 seconds.

Assembly of Prints

The templets having been cut, the assembly is the next step. If possible it is advisable to fasten sufficient composition boards on a platform to permit the layout of the entire area at one time. In that way coordinates may be plotted on the boards by using two transits, or by very careful measurement and marking and the location of the known control points that are to be used. The selection of the proper control to accomplish the accuracy required is important, and it is essential that the control used be such that the points may be accurately identified on the aerial pictures. If a control point is improperly plotted or identified, the layout in the vicinity of that point will not be possible because the templets will not fit.

Posts are now fastened over the plotted control points by nailing in place. Each post has a hole drilled through the center. When a Bankers pin is placed in such a hole and driven into the board it locates the center of the post as well as the center of the slot in which the post moves. It is now possible to assemble the templets, placing posts so that all the slots corresponding to radial lines to the same image point fit over a post and when a control point is reached the slots to that particular image point are placed in these instances over the fixed post. The assembly of templets may need to be expanded or contracted to fit the control post but this is no problem because the other posts are free to move as dictated by the intersecting slots from overlapping templets.

The number of control points required for a given accuracy is much smaller than for other systems because the mechanical nature of the slotted-templet system holds each intersection of the radial lines far more rigidly than is possible by merely drafting on transparent material and adjusting manually, depending on some form of tape to hold the templets in place.

ACCURACY OF METHOD

As to the accuracy that may be secured, it is difficult to express in terms of feet on the ground or distance on the finished map, as it is affected by the scale of the original aerial pictures, the scale of the finished map or mosaic, the nature and amount of control as well as the terrain being covered. The error may be expressed in distance from true position in hundredths of an inch and the spacing of control by the number of prints between points; for example, if control is every fifth print in line of flight and in every two-flight lines 85 per cent of any points on the map will be within two hundredths of an inch of true position, and the remaining 15 per cent within four hundredths. If an accuracy of eight hundredths of an inch for 85 per cent of any points on the map and fourteen hundredths for 15 per cent of any points is satisfactory, control may be on every twenty-fifth print in line of flight and every tenth strip.

This method enables one to estimate the accuracy based on scale of the original negatives and the distance in feet based on the scale of the map. Consideration must be given to the overlap of the prints, which is usually 55 per cent in line of flight and 30 to 40 per cent side overlap between strips.

Expressing it in another way, based on a definite set of conditions, if the original negatives are at a scale of 1 in. = 2640 ft. (1:31,680) and the control points are spaced 30 miles apart, the average error for points anywhere on the map will be 110 ft. from true position and the maximum error will be 170 ft. If greater errors are permissible, as in reconnaissance maps of large areas, control may be still more widely scattered, as much as one control station for each 1000 sq. miles of area.

An aerial photographic mosaic map does not need to be made to take advantage of the method, as it is possible to make a plot map giving the plotted position of the center of each photograph in an area. This method is especially valuable when it is desirable to take contact prints into the field, and by ground exploration plot on the pictures detailed information, such as geology. After this work is finished, perhaps in isolated sections, the data shown on each print may be plotted on the map in correct position in relation to the control of the entire area. In this way various parties may work on a project, yet their findings and notes may be plotted at a central point, keeping each bit of data in the correct location without going to the expense of always correlating the field discoveries to some control point, which may be difficult to accomplish, especially in jungle or rugged terrain.

Further details regarding the slotted-templet method may be secured from U. S. Patent No. 2102612 (Dec. 21, 1937).

The New Wide-angle Aerial-survey Camera

By A. W. Furbank,* Member A.I.M.E.

(New York Meeting, February, 1938)

In reviewing the aerial cameras produced in different countries, it becomes apparent that in nearly all of them an attempt has been made to secure the greatest possible angle of view. This angle, of course, is determined by the objective. The objectives most commonly in use in aerial cameras have a maximum angle of 65°. The objective developed for this new Zeiss camera combines freedom from distortion and brilliant definition, with an angle of 95°. Aerial mapping, it is claimed, has been placed on a different economic basis, and new possibilities presented, particularly in connection with automatic stereoscopic plotting instruments, to which some short references are made.

One way of enlarging the angle of view is to couple several instruments with their axes convergent, thereby producing a multilens camera. Typical of cameras of this sort in the United States is the Bagley four-lens camera, which later was developed into the five-lens camera (T3-A) of the U. S. Air Corps. More recently, in order to get away from the unfavorable Maltese cross image field of the five-lens camera, and to obtain a more practical form, two five-lens cameras were combined. By using them in tandem and rotating them by 45° relatively to each other, a ten-lens camera was produced, covering an octagonal ground area, with a total angle of view of 140°. Similar designs have been evolved in other countries. In all of them, however, a number of difficulties have arisen, quite apart from their large weight and high cost. Because of their complex mechanism, numerous shutters and magazines, and the high precision with which these parts must be interadjusted and synchronized, these cameras are far from dependable.

Moreover, a multilens camera by itself does not yet constitute a complete outfit for producing pictures suitable for photogrammetric survey. Because all the component pictures, except the central one, are obliques, it is always necessary to employ rectifying apparatus which transforms the marginal views to the perspective of the central one. In multilens cameras with many individual magazines, it is not convenient to

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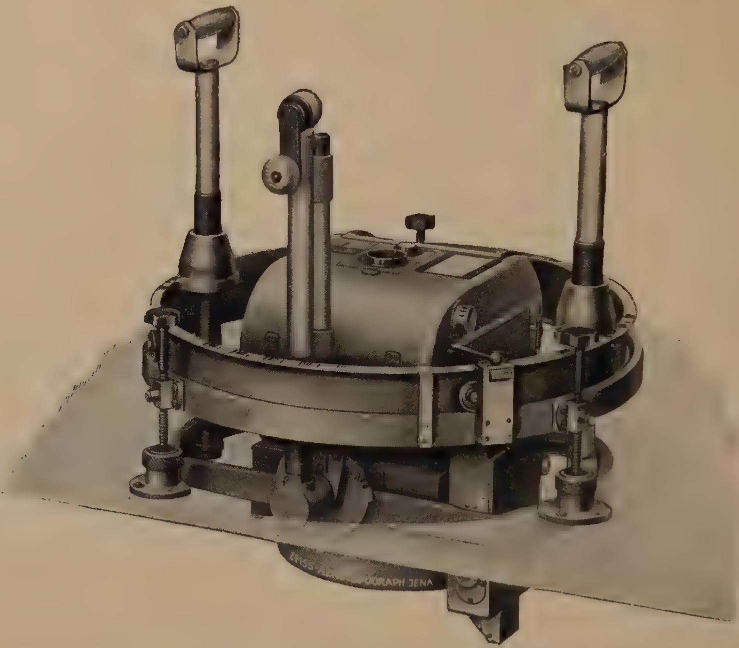

FIG. 1.—ZEISS-AEROTOPOGRAPH WIDE-ANGLE CAMERA.

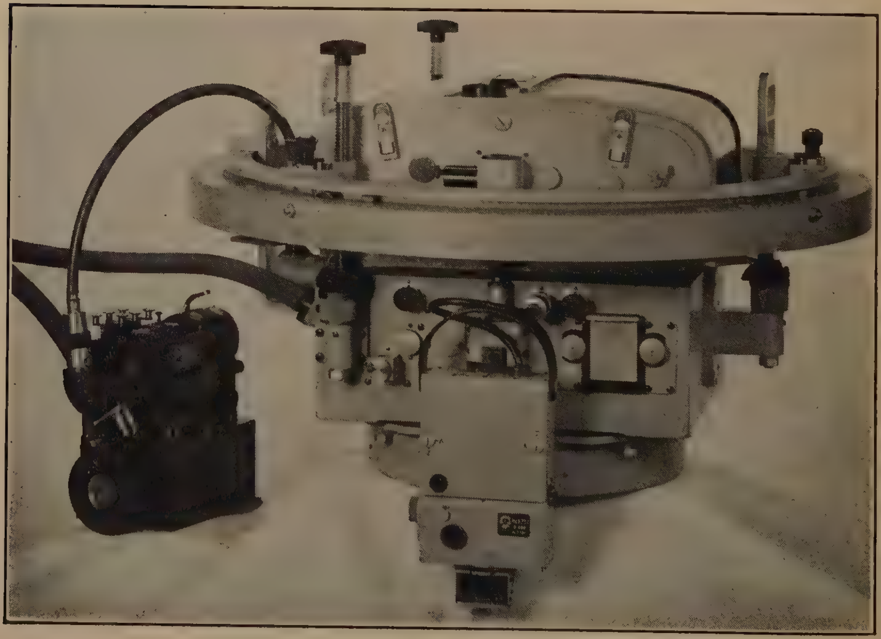

FIG. 2.—SAME KIND OF CAMERA AS IN FIG. 1, BUT LARGER.

employ "revolver" rectifiers.* Accordingly, each component view must be rectified by itself, and thereafter the several views assembled by a mechanical process. The accuracy of these mechanically composed, rectified photographs no longer meets modern standards. This limitation has led to the construction of multilens cameras that permit photographing the several views on a single film, so that the rectification and "joining up" of the several views can be effected in one operation on revolver rectifiers. The nine-lens camera, developed by the U. S. Coast and Geodetic Survey, belongs to this latter type. The problem has been solved by deflecting the lateral images with the aid of steel mirrors placed in front of the objectives. Yet the transforming process remains lengthy and involved even where revolver rectifiers may be used, because it is absolutely necessary to effect careful photographic compensation in the obliques surrounding the central view, in order to obtain a picture of at least tolerably uniform photographic qualities. Added to these troubles is the fact that a truly gapless combination of the component views—speaking from the viewpoint of photogrammetry—is obtained only in rare instances.

A further limitation lies in the fact that the theoretical angle of view obtained with multilens cameras is of questionable value if it greatly exceeds 90°. With excessive angles the quality of the marginal portions of the transformed component photographs leaves much to be desired. Experience shows that after passing a vertical angle of 45°, numerous dead angles occur, while even small obstructions and elevated objects such as houses and trees produce unpleasant gaps toward the margin. The identification of detail becomes uncertain, because all vertical objects appear radially tilted—a most troublesome condition, especially in geological work. It is no longer possible to estimate the slope of terraces, declivities and other geological features involving elevations. When maps are produced from such photographs, differences in level easily result in errors in position of the order of magnitude of the differences themselves, and rapidly grow larger after an angle of 45° has been passed. The most favorable condition is obtained, particularly for simple and direct evaluation, if an angle of about 90° is not exceeded.

The firm of Zeiss-Aerotopograph accordingly abandoned further work on multilens cameras when they had succeeded in obtaining a rapid objective, which combined freedom from distortion and sharp definition with an angle of view of 95°.

The new Zeiss wide-angle aerial objective is known as the "Topogon." It has an aperture of *F*/6.3 and is made in two focal lengths, 10 and 20 cm. (4 and 8 in.) for small-scale and large-scale work respectively. Fig. 1 shows the Zeiss-Aerotopograph wide-angle camera, model

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* It is understood that there is one exception; namely, a rectifier designed in the United States for the Zeiss-Aerotopograph four-lens camera.

RMK-P-10/1818, which uses the 10-cm. Topogon on 18 by 18-cm. (7 by 7-in.) film. The image covers a circle of 8⅜-in. diameter, so that the extreme corners of the 7 by 7-in. square remain empty.

The objective is fitted with between-lens, multiblade precision shutter, giving exposure periods between $\frac{1}{25}$ and $\frac{1}{250}$ sec.

The equipment, including the mounting and 200 ft. of film in standard magazine, weighs only about 90 lb. Its installation in the airplane presents no difficulties; it is only necessary to provide a hole in the floor large enough to utilize the wide angle of view. The camera itself is carried in a gimbal suspension, in a mounting designed to permit setting the drift angle, and fitted with spring buffers as a protection from vibration. It can if desired be tilted mechanically in the mounting by 20° to either side. This addition to the angle of view is sometimes of value for general survey. The camera can also be lowered far enough so that the auxiliary prism is not obstructed by the fuselage when using the horizon camera described below.

Fig. 2 shows model RMK-P-20/3030 of the wide-angle camera. It is much the same as the first, except that it is larger and intended for large-scale mapping. It is only slightly heavier than the smaller model; the complete equipment, including mounting and loaded magazine, weighs only 155 lb. The illustration shows the camera in the mounting suitable for vertical exposures and permitting drift compensation. The model is also available in special mounting for vertical and oblique views, but without drift compensation. It uses a 20-cm. Topogon and covers 30 by 30-cm. (12 by 12-in.) film. An electric drive with variable-speed gear is standard equipment for the larger model. Steplessly variable electric drive is usually preferred for the smaller model. Besides, outboard airscrew drive is available for either camera and in all cases an additional manual drive is provided as a standby. A view finder with built-in intervalometer is operated either by airscrew or electric drive. The correct overlap of successive views is automatically secured by bringing the rate of the traveling marks in the intervalometer into step with the passing ground image. The film is flattened by slightly compressed air from a blower.

Simultaneously with each exposure, orientation marks are photographed on the film by mechanical stencils on the focal plane frame, and also the position of a bubble, the dial of a clock, the face of a counter, and the serial number and focal length of the camera.

Tests[1] have shown that, with automatic equipment, aerial surveys can be carried out in an extremely economical way when certain accessories are used on the camera for fixing the external orientation of the views on the picture itself. These orientation data consist of the difference in altitude between adjoining exposures, and the angle of tilt. When these are known for each picture, the ground covered by a flying strip can be reconstructed in a simple manner, and it becomes possible to bridge with a dependable degree of accuracy long stretches of ground lacking control points.

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[1] See *Ztsch.* deut. Gesellschaft Photogrammetrie (1935) No. 4.

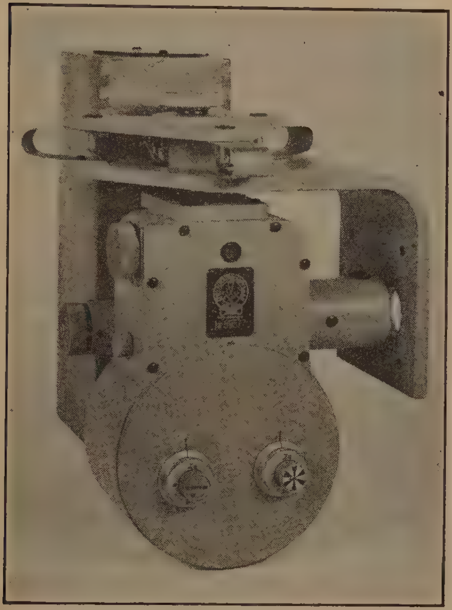

Fig. 3.—Recording camera with statoscope.

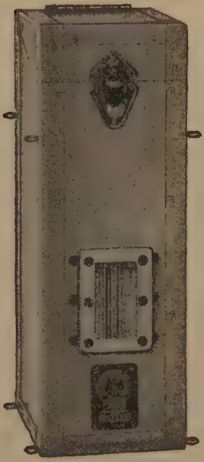

Fig. 4.—Statoscope.

The accessory automatic equipment referred to consists of the horizon camera and the statoscope recording camera with statoscopes (Fig. 3). The statoscope alone is shown in Fig. 4. It is a differential barometer, which enables the pilot to correct deviations in flying height. Photographic statoscopic records at each exposure of the main camera permit determination of the difference in altitude between successive exposures with an accuracy of about ±3 ft. (Fig. 5). The horizon camera (Fig. 6) is also connected with the main camera. It photographs the horizon simultaneously with the main exposure and thus permits determination of the angular position at the instant each picture is taken. The shutters of the two accessory cameras are connected with the main shutter by electric contacts. Fig. 7 represents a view taken with the horizon camera. The view is pointing aft, and the tail skid can be seen.

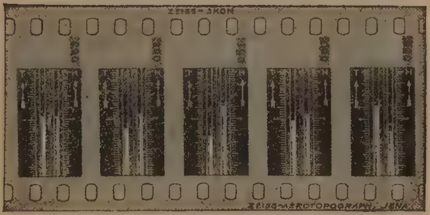

Fig. 5.—Statoscope record.

The need for bridging spaces that lack control points arises in almost all geological exploration. While methods like those customary in the

United States, such as the radial line method, permit graphic triangulation of limited accuracy, they afford no information whatever on elevations. Aerial triangulation with automatic plotting instruments, on the other hand, supplies the topography in addition to the elevation, and this with a very much greater degree of accuracy, in less time, and with very little calculation.

Photographic Records

It has been found in practice that for general geological prospecting and mapping, as well as for planning projects, a picture scale of 1:30,000 to 1:40,000 is sufficient, whereas for the subsequent detail mapping of selected regions a scale of about 1:10,000 is required. The picture scale number is found by dividing the altitude by the focal length; multiply the height in meters by 100 and divide by focal length in centimeters. Picture scale, altitude and camera focal lengths are related as shown in Table 1. At an altitude of about 13,000 ft., with a picture scale of 1:40,000, the width of the strip photographed by the wide-angle camera is about 4.3 miles, and the area per picture about 18 sq. miles. The stereoscopic picture resulting has a high degree of "plasticity."

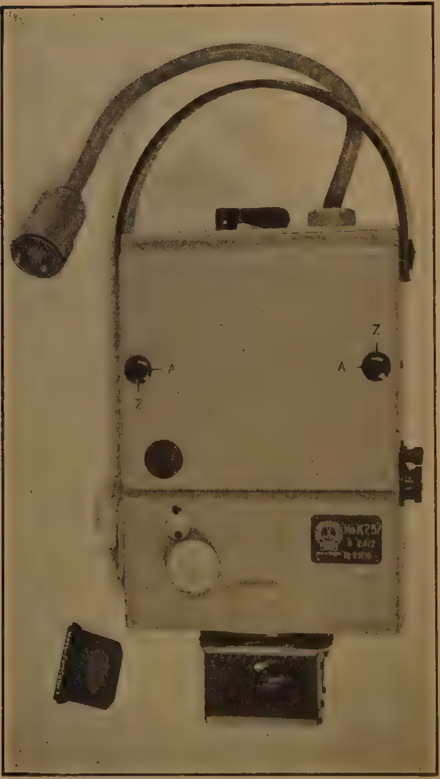
Fig. 6.—Horizon camera.

Fig. 8 shows the Multiplex Aeroprojector, a stereoscopic plotting apparatus giving simultaneous spatial projection of several aerial photographs in a given series. It is normally used for plotting only from approximately vertical photographs, and is particularly suitable for making maps of about 1:25,000 and smaller. It has great uses in the simple application of methods of considerable precision to the bridging over of spaces that are deficient in ground control points. The following is an abstract of a description of it given by Capt. L. J. Rumaggi, of the U. S. Corps of Engineers:

> The Multiplex Aeroprojector is a stereoscopic plotting instrument utilizing aerial photographs in the compilation of topographic maps. It is the simplest type of the

various machines heretofore designed for this purpose, based as it is on the principles of direct optical projection of the two overlapping photographs covering a certain area.

The anaglyphic principle is used in effecting separation of the two images, which means that the photographs are projected in space in complementary colors, and by using filters of like colors, worn over the eyes, only the red image is seen through the red filter and the green image through the green filter. The resulting projection then is an image in three dimensions as seen on an intercepting screen just as certain motion pictures appear when viewed through colored spectacles.

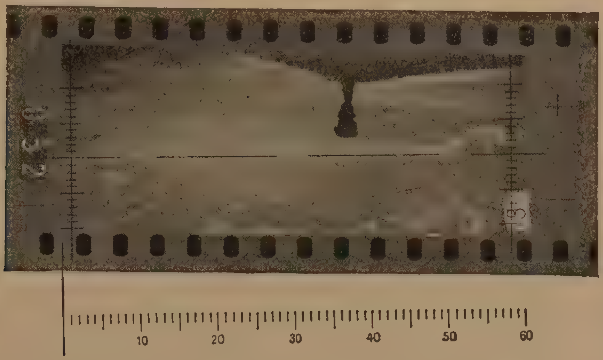

FIG. 7.—VIEW TAKEN WITH HORIZON CAMERA.

In operation, the apparatus consists of a bar from which are hung two or more miniature aerial cameras. The image is projected on a screen which can be moved in the three directions. There exists on the screen a mark which is moved about to touch the features of the earth as projected. Immediately below the mark is a drawing pencil which traces on the map sheet the outlines and courses of these features. Thus the courses of streams, the outlines of woods, the position and shapes of houses, the right of way of roads and railroads are placed on the map. The hill and valley shapes are shown as contours or lines of equal elevation above sea level and are drawn by moving the table while the mark, set at a fixed elevation, is kept in contact with the ground.

TABLE 1.—*Relation of Picture Scale, Altitude and Focal Length*

Scale 1:35,000				
Focal length, cm	5	10	15	20
Flying height, ft	5,700	11,500	17,000	23,000
Scale 1:10,000				
Focal length, cm	5	10	15	20
Flying height, ft	1,650	3,300	5,000	6,600

The photographic information is placed in the machine in the form of reduced transparent positive plates, which are made from the original negatives by an accompanying projection printer. The glass plates are in reality small lantern slides.

The cameras can be moved about on their supporting bar until they again occupy in space, to scale, the positions of the aerial camera at the moment of the individual exposures. Thus the effects of bouncing and pitching of the aeroplane on the photograph are accounted for.

The determination of these positions of the aerial camera is accomplished by making all portions of the overlap in the two photos come into steroscopic fusion and the resultant moulded image of the earth's surface is then shifted about in space to fit it to the ground.

With this type of equipment it is possible to make maps of areas without the operator actually seeing anything but the photographs, and maps have been made in Ohio of portions of the state of Washington, without any of the operators having seen the area to be mapped.

The map thus prepared is usually a better one than could be prepared for the same cost by the methods formerly used.

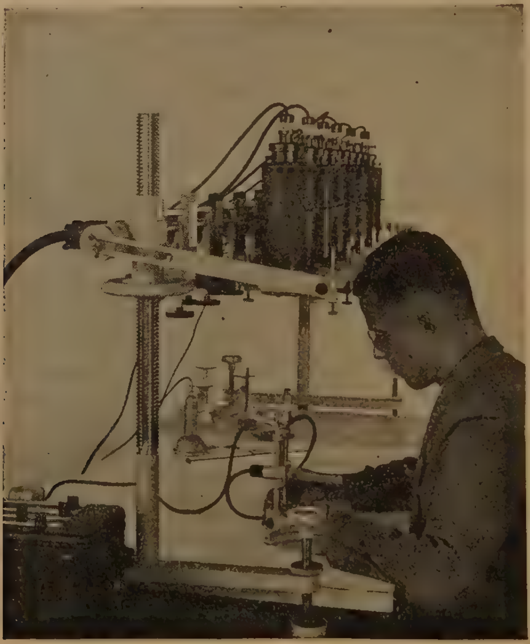

FIG. 8.—MULTIPLEX AEROPROJECTOR.

Fig. 9 shows the very elaborate instrument known as the Zeiss Stereoplanigraph. In regard to its operation, the makers state:

> When a landscape is photographed the light rays from the individual points in the terrain pass through the objectives of the cameras and produce image points on the sensitized surface. In the Stereoplanigraph the path of the rays is reversed. They leave the illuminated image points, pass through the projection systems of two cameras and produce a scale model or relief picture of the landscape. A tracing mark stereoscopically viewed is made to run over this model during stereoscopic observation and the tracing movements of the mark are automatically registered on a drawing table. The vertical movement is read on an altitude counter. The plotting scale can be varied quickly and easily within wide limits independently of the photo scale, and the altitude counter is so designed that it may be read directly to the plotting scale. The projection cameras (picture carriers) have focal lengths and sizes corresponding with those of the photographic cameras.

A specially valuable feature is the ability of the Stereoplanigraph to plotting exposures from two-lens cameras and wide-angle cameras. For this purpose suitable plotting cameras are used and these give the orientation and measuring just as easily as with single camera exposures.

All adjustments of cameras and tracing marks are effected, and readings taken, by the observer without leaving his seat. The unknown mutual orientation of the cameras is quickly found by a systematic procedure involving no calculation. The absolute orientation is secured more quickly owing to the fact that both cameras can be tilted about a common axis and inclined together.

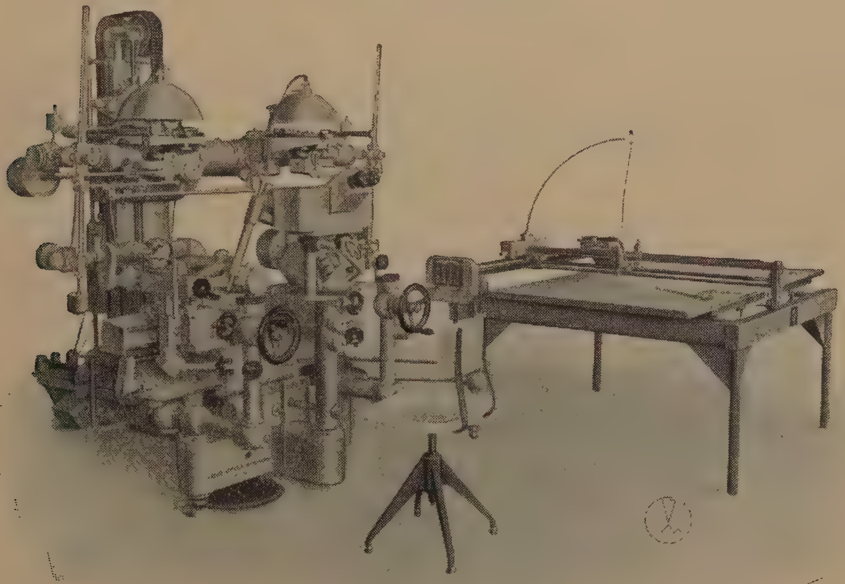

FIG. 9.—ZEISS STEREOPLANIGRAPH.

The Stereoplanigraph is also fitted with the special device for stereoscopic interchange to allow of continuous plotting of photographic series exposures and to bridge over, by aerial triangulation, stretches having no ground control points. This provision for the plotting of series confers a further advantage when dealing with exposures from two-lens and wide-angle cameras.

FIELD PRACTICE

The first extensive geological exploration of concession territories with the aid of photogrammetry was carried out by the Niederlaendisch Neu Guinee Petroleum Co. in New Guinea in 1935 to 1937. Similar projects of the Shell company are under way in Sumatra, Borneo, Venezuela and Colombia. The concession territory that had to be geologically explored and mapped at a scale of 1:25,000 comprised 37,500 square miles. The maps were needed to determine the location of deposits and subsequently to fix the exact boundaries of the territory embraced by the concession. Work was started simultaneously with a nine-lens camera of 5.5-cm. focal length and with several 10-cm. RMK-P-10/1818 single-lens wide-angle cameras. In the process of work, experience showed that because of the disadvantages mentioned above as inherent in multilens cameras, the nine-lens camera was of little service, and it was therefore withdrawn from the project at an early stage.

After extensive tests, a picture scale of 1:40,000 was adopted for photographing with the RMK-P-10/1818 cameras, requiring a flying height of about 13,000 ft. above the ground. Photographic statoscope records were used with the cameras in order to simplify the subsequent triangulation in automatic plotting instruments such as the Multiplex and Stereoplanigraph.

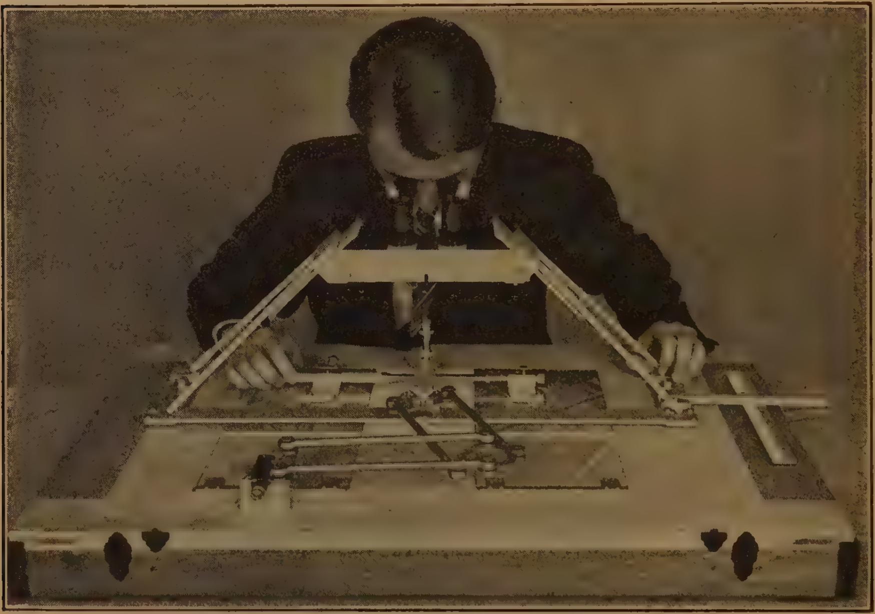

FIG. 10.—FOLDING MIRROR STEREOSCOPE.

In the earlier part of the work the geodetic relation between the consecutive views of a strip and between adjoining strips was established by radial triangulation and the graphic radial method. Later the more economical and precise methods of aerial triangulation by means of the Stereoplanigraph and the wide-angle Multiplex were used.

"Photogeologists" carried out the topographic detail mapping proper, together with the geological analysis, with the aid of Zeiss-Aerotopograph folding mirror stereoscopes equipped with tracing stereometers and parallel guides, as shown in Fig. 10. These instruments are of great value for quick mapping on a small scale, and for rapid filling in of details on existing maps. Thus a geological morphological map 1:25,000 was produced in several colors and printed. Several of these sheets, reduced to a scale of 1:100,000, were combined on a single sheet for field use.

Occasional small trips offered to the photogeologists an opportunity to compare the geological details found in the photographs with the corresponding features in nature, and at the same time expanded and improved the morphological "key" for reading the aerial photographs. The "index map"—a sort of mosaic plan, obtained as a by-product from the views taken with the RMK-P-10/1818—rendered most valuable aid in the ground work of the geologists and in navigating the flights. Stereoscopic aerial pictures, together with the stereoscopes required for viewing them, formed supplementary equipment on these trips and greatly aided the field work.

The Environment of Ore Bodies

DISCUSSION

[Refers to the paper by Edward Wisser, which appears on pages 96 to 110 of this volume.]

R. P. Jarvis,* El Oro, Estado de México, México.—The practical problem raised by Mr. Wisser—that is, the determination of the lower limit of ore deposition, below which it is useless to look for ore shoots—is one of the most important in economic geology. He asks: "Can we learn to determine the position of such a line?" For individual districts, yes; but its determination has always been by empirical methods; that is by actually exploring the veins to such depths that the values drop below the economic limits. Usually the signs are plain enough that values have been bottomed without confirmation by the chemist or assayer. Most veins, when approaching their limit, begin to split into branches or stringers; the vein matter itself undergoes a change from "lively looking" rock to one that is dull and unpromising; the quartz, instead of having segregated into clean vein matter, has simply spread itself into the country rock, rendering this more siliceous but no richer—these, together with inclusions of the country rock in the vein, are all positive indications of the limit.

Mr. Wisser seems disposed not to accept the law of cause and effect, which he calls "empiricism." He says: "Empiricism embodies an assumption perhaps not evident at first glance. It is this: that like effects spring from like causes and therefore necessarily have a common meaning." There can be no doubt as to the validity of this law, since it is the foundation stone upon which are built all inductive sciences, including economic geology. When demonstrable, proved facts become confused with inferences, as they seem to be generally in the paper under examination, no sound conclusions can be reached.

Mr. Wisser has failed to give sufficient data covering the two vein systems which he cites as examples. Presumably they are situated in the Pachuca District of Mexico, but not everybody is familiar with the vein systems there in spite of the fact that it is world famous as a silver producer. Are these two systems separated some distance horizontally from one another and how far? He has given no estimate of the amount and kind of rock that has been eroded from over the present veins. His description of the two systems appears on page 100, beginning: "1. East-west veins," and ends on page 101, "they would lack spaces there in which to deposit."

On page 101, with the paragraph beginning "On the other hand," he gives a picture of what he believes takes place in class 2 veins.

The sum of this seems to be, according to Mr. Wisser's observations, that, in the east-west veins, class 1, there has been an invasion of an "altering solution," which I judge has been responsible for the formation of extensive "alteration haloes"; that these alteration solutions have followed along pre-existing fractures or fissures; and that after these alteration solutions finished their work the mineralizing solutions deposited the vein matter and metallic values. Mr. Wisser does not specify clearly what the "alteration haloes" consist of; in other words, what change the original rock has suffered, whether oxidizing, carbonating, or sulphidizing. If they came from depth they could not be oxidizing or carbonating, and in this case it is a bit difficult to understand what change could have been produced in the original rock. Mr. Wisser then assumes that, following the preparatory work of the altering solutions, there was an invasion of the mineralizing solutions, and that these followed in the same channels as the first. In that case, is it not a fair inference that they must proceed from the same source? He assumes that the fractures remain open during the entire period of alteration and mineralization; that is, for uncounted aeons. At this point it might be well to ask Mr. Wisser if, in his examination of these veins, he has found extensive open channels underground; or whether he merely assumes there must have been such open channels because the vein matter appears to fill a fracture or fissure? Apparently, the more extensive the "alteration haloes" the larger the ore deposits; although the relation between the volume of altering solution and the mineralizing solutions is not clear, unless they happen to be the same. Possibly they are. The place where deposition takes place seems to be somewhat optional with the solutions themselves. He says, to repeat: "If these fractures had squeezed shut in the soft breccia before the time of vein formation, ore shoots would avoid the breccia *because they would lack spaces there in which to deposit.*"

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* Consulting engineer.

Coming to his north-south veins, class 2, apparently his altering solutions play only a minor role and there are no large "alteration haloes." The veins evidently are "tight" and there have been no large open spaces where ore shoots have formed. The small amount of altering solutions have followed different channels from the mineralizing ones. On the whole Mr. Wisser assumes that the conditions responsible for the formation of class 1 veins were quite different from those causing the formation of class 2, and yet the two classes of veins are about equally strong. Rather curious that within such a restricted area altering solutions and mineralizing solutions should elect to differ so radically in their choice of channels.

On page 105, third and fifth paragraphs, on page 106, second and third paragraphs, and on page 108, beginning with the eighth line from the bottom of the page, Mr. Wisser gives descriptions and uses nomenclature not in accordance with "facts" and usage accepted by most geologists in the field, and with which I am in sharp disagreement.

E. Wisser (author's reply).—The completeness with which Mr. Jarvis has missed the point of the paper under discussion is disquieting, and implies faulty presentation, to Mr. Jarvis at least, so that this chance for clarification is welcomed.

This paper did not attempt to answer the question propounded in the Symposium on Mining Geology at the New York meeting in February 1938, concerning the determination of the lower limit of ore deposition. I attempted to answer that question in a later paper.* The paper discussed here dealt with a general subject, the nature of criteria related to ore occurrence, and the interrelation of fact and inference in scientific thinking. No theory of ore formation was formulated, and the examples cited could be entirely mythical without in any way affecting the argument advanced. Fortunately, Mr. Jarvis proceeds to answer the symposium question out of hand, and states: "Most veins, when approaching their lower limit, begin to split into branches or stringers," etc. (see page 426). In the paper he criticizes, I say (p. 97): " . . . the change (i.e., that marking the lower limit of ore-body expectancy) might be from 'live looking' quartz characteristically associated with ore to dead silicification quartz, a feature frequently found in veins below their productive horizons." Also, in the later paper cited (p. 144): "As the roots of precious-metal ore are approached, the complexity of the vein structure increases . . . silicification and replacement are often intense at such horizons." Thus for a certain type of vein (epithermal precious metal) Mr. Jarvis and I agree on behavior in depth.

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* Page 140, this volume.

I am next accused of flouting the law of cause and effect. Under controlled laboratory conditions, the environment of an experiment is stabilized, and like causes produce like effects. Further, we see the experiment in operation. In the study of ore deposits, we see only after-effects of processes, never the processes themselves. But since we do not see the processes, we may only infer their nature from things we can see, and the point I made throughout my paper was that where environments of mining districts are but imperfectly known effects that seem alike to us may have sprung from unlike causes, and may have radically different meanings in terms of ore. Herein lies a pitfall in the use of empirical criteria.

INDEX

(Note: In this index the names of authors of papers and discussions and of men referred to are printed in small capitals, and the title of papers in *italics*.)

A

Aerial photographs: cameras used, 359, 415
  conditions for success, 357
  geologic maps: Clifton-Morenci area, Arizona, 366
    coal-bearing area, 392
    gas field, 400
    Mother Lode area, California, 384
    oil-field area, 396, 401, 406
    Ray area, Arizona, 372
    San Francisco volcanic area, 390
    Ship Rock area, New Mexico, 385
    Silver City area, New Mexico, 378
  use in geologic mapping: brief bibliography, 408, 409
    mounting, 360
    slotted-templet method, 410
    stereoscope: role in viewing maps, 408
Anza line: definition, 64
Aguilar lead-zinc mine, Argentina: principles governing deposition of ore, 126, 251
Arizona. *See* Clifton-Morenci, Ray, San Francisco
Avery Island: aerial map, 406

B

Bain, G. W.: *Geological, Chemical and Physical Problems in the Marble Industry*, 324
  Discussion on Ore Search, 127
Balmat mine, New York: principles governing localization of ore, 126, 253
Barite deposits: deposition controlled by structure and rock composition: Cartersville, Georgia, 276
  northern Nevada: geology, 294
    location, 295
    origin and age, 299
    production, 294
Barr, H. L. and Gardner, D. L.: *San Mauricio Mining Company, José Pañganiban, Camarines Norte, P.I.*, 190
Bateman, A. M.: *Discussion on Ore Search*, 120
Behre, C. H. Jr.: *Discussion on Ore Search*, 118, 123, 131
Billingsley, P.: *Discussion on Structure of Ore Districts in the Continental Framework*, 59, 64
Billingsley, P. and Locke, A.: *Structure of Ore Districts in the Continental Framework*, 9
Bisbee ore district: geology, 21
Bsmuth minerals: Leadville, Colo., 265
Blowout: in ore deposits: example, 136
Boutwell, J. M.: *Discussion on Ore Search*, 139,
Broderick, T. M.: *Discussion on Ore Search*, 121, 138
Brown, J. S.: *Factors of Composition and Porosity in Lead-zinc Replacements of Metamorphosed Limestone*, 250
  Discussion on Ore Search, 126
Bruce, E. L.: *Discussion on Ore Search*, 129

C

California. *See* Mother Lode.
Cameras: aerial photography: single lens and multilens, 359
    wide-angle, 417
Carbon dioxide: commercial accumulations: occurrence, 225
  in geologic structures: areas favorable to development of commercial production, 235
    brief bibliography, 248
    estimation of reserves, 244
    Farnham anticline, Utah, 239
    Niland, Imperial Valley, California, 243
    occurrences known, 223
    United States: distribution, 224
    Wagon Mound anticline, New Mexico, 241
  in igneous rocks, 231
  in volcanic gases, 228
  occurrence in nature, 225
  origin, 230
Cartersville district, Georgia: geology, 276
  minerals produced, 276
  ore deposition: brief bibliography, 292
  ore deposits: deposition affected by rock composition, 276
    structural control, 279
Chapman, E. P.: *Newly Recognized Features of Mineral Paragenesis at Leadville, Colorado*, 264
Clarke, R. H.: *Discussion on Ore Search*, 123, 130
Clifton-Morenci area, Arizona: aerial map, 366
Coal measures: aerial photograph, 392
Colorado. *See* Leadville.
Columbia River basalt: relation to gold quartz veins, 179
Continental framework: United States: structure of ore deposits, 9

Copper-zinc deposit: Teziutlan, Puebla, Mexico: geology, 314
  mineralogy, 322
  mining and milling, 316
  origin, 322
  petrology, 317
  structure of ore bodies, 319
Core drill: large-diameter: damsite exploration, 345
  equipment, 340
  geologic exploration: brief bibliography, 351
    use, 340, 343
  Prettyboy Dam, 353
  technique, 341
  use in grouting operations, 345
  use in slate, 354
  use with wire saw, 352
  uses, 340 et seq.
Cornucopia, Oregon: geology of gold quartz veins, 172

D

Damsites: exploration with large-diameter core drill, 345, 353
Dougherty, E. Y.: *Discussions: on Geology of the McIntyre Mine*, 169
  on Ore Search, 137
Drill: core. *See* Core Drill.

E

Edelen, A. W. and Lee, H. V.: *The Teziutlan Copper-zinc Deposit, Teziutlan, Puebla, Mexico*, 314
Edmundson, R. S.: *Discussion on Barite Deposits of Northern Nevada*, 299
Ely ore district: geology, 33
Environment of ore bodies. *See* Ore Deposits.
Eureka ore district: geology, 30

F

Forrester, J. D.: *Discussion on Ore Search*, 114
Fowler, G. M.: *Discussion on Ore Search*, 112, 116, 121, 131, 132
Fox, P. P. and Moneymaker, B. C.: *Large-diameter Core Drill for Geologic Exploration*, 340
Furbank, A. W.: *New Wide-angle Aerial-survey Camera*, 415

G

Gardner, D. L. and Barr, H. L.: *San Mauricio Mining Company, José Pañganiban, Camarines Norte, P.I.*, 190
Geologic mapping: structure of ore deposits, Continental framework, United States, 9
  use of aerial photographs, 356
Geologist: aid he can give in solving problems of marble industry, 324
Geology (*see also* Ore Deposits; Rocks): Anza line: definition, 64
  basement: meaning of term, 63, 64
  cover: meaning of term, 63
  regional patterns, 40, 42
  structure of ore districts in the Continental framework, 24
  tear fault: term used with various meanings, 62, 64
  Walker line of tear faults, 61
Georgia. See Cartersville.
Getchell mine, Nevada: geology, 147
Gianella, V. P.: *Barite Deposits of Northern Nevada*, 294
Gidel, M. H.: *Discussion on Ore Search*, 114
Gold deposits: geology: Getchell mine, Nevada, 147
    McIntyre mine, Ontario, 151
    quartz veins: Cornucopia, Oregon, 172
    San Mauricio mine, Philippine Islands, 190
  influence of structure of vein on richness of deposit, 119
  migration of mineralizing solutions at Privateer mine, B.C., 117
  origin: placer theory and infiltration theory, 118
  San Mauricio mine, Philippine Islands, 190
Goldfield ore district: geology, 36
Gold milling: San Mauricio, Philippine Islands: equipment, methods and costs, 190, 213
Gold mines: San Mauricio, Philippine Islands: development, equipment, methods and costs, 190, 208
Gold mining: San Mauricio mine, Philippine Islands: methods and costs, 208
Gold quartz veins: Cornucopia, Oregon: geology: brief bibliography, 188
  geology: Cornucopia, Oregon, 172
Goodspeed, G. E.: *Geology of the Gold Quartz Veins of Cornucopia*, 172
Goodsprings ore district: geology, 13
  Walker-line faults, 61
Granite: effect of acid on iron-rich mica content, 128
Graton, L. C.: *Discussion on Ore Search*, 121, 128
Grouting: large-diameter core drill a help, 345

H

Hamilton, S. H. *Discussion on Large-diameter Core Drill for Geologic Exploration*, 354
Hardy, R. A.: *Geology of the Getchell Mine*, 147
Hedley ore district: geology, 28
Hoffman, R. D.: *Discussion on Ore Search*, 120
Huitzuco, Guerrero, Mexico: mercury deposits, 300

I

Iron ore: brown: deposition controlled by structure and rock composition: Cartersville, Georgia, 276

J

Jarvis, R. P.: *Discussion on The Environment of Ore Bodies*, 426
Joralemon, I. B.: *Discussion on Ore Search*, 121, 132

K

Kelly, S. F.: *Discussion on Ore Search*, 125, 145
Kesler, T. L.: *Structure and Ore Deposition at Cartersville, Georgia*, 276
Killas, definition, 130

L

Langford, G. B.: *Geology of the McIntyre Mine*, 151
  Discussion on Ore Search, 123, 139
Lava: effect on gold quartz veins: Cornucopia, Oregon, 179
Leadville, Colo.: mineral paragenesis: bismuth stage, 265
    brief bibliography, 275
    new features, 264
  structure of ore deposits, 24
Lead-zinc deposits: principles governing localization of ore, 126, 251, 257
  replacements of metamorphosed limestone: factors of composition and porosity, 250
Lee, H. V. and Edelen, A. W.: *The Teziutlan Copper-zinc Deposit, Teziutlan, Puebla, Mexico*, 314
Locke, A. and Billingsley, P.: *Structure of Ore Districts in the Continental Framework*, 9
Loel, W.: *Use of Aerial Photographs in Geologic Mapping*, 356; *discussion*, 409
Loughlin, G. F.: *Discussion on Ore Search*, 128, 135

M

Manganese deposits: oxide: deposition controlled by structure and rock composition: Cartersville, Georgia, 276
Mapping. *See* Geologic Mapping.
Marble: effect of salt solutions, 328
  some types: coefficients of irregularity, 331
Marble industry: chemical problems, 326
  geological problems, 324
  geologist can help in solving chemical and physical problems, 324
  physical problems, 334
  waste utilization, 334
McIntyre mine, Ontario: geology, 151
McKinstry, H. E.: *Structural Control of Ore Deposition in Fissure Veins*, 65; *discussion*, 93
  Discussion on Ore Search, 116
McLaughlin, D. H.: *Discussion on Ore Search*, 118
Mercury deposits: Huitzuco, Guerrero, Mexico: genesis, 311
Mercury deposits: Huitzuco, Guerrero, Mexico: geology, 302
    history, 301
    production, 301
Mercury mining: methods at Huitzuco, Guerrero, Mexico, 311
Mexico. *See* Mercury Deposits, Copper-zinc Deposits.
Meyer, W. H. Jr.: *New Method of Mapping with Aid of Aerial Photographs and Slotted Templets*, 410
Miller, J. C.: *Carbon Dioxide Accumulations in Geologic Structures*, 222
Moneymaker, B. C. and Fox, P. P.: *Large-diameter Core Drill for Geologic Exploration*, 340; *discussion*, 355
Montana Echelon gap: regional pattern, 42
Mother Lode area, California: aerial map, 384

N

Natural gas: aerial map of Buttonwillow field, 400
Newhouse, W. H.: *Discussion on Ore Search*, 123
New Mexico. *See* Ship Rock; Silver City.

O

Oil lands: aerial photograph, 396, 401, 406
Ore deposits (*see also* Geology; Rocks):
  alteration haloes, 100, 426
  bedding-plane faults important, 124
  blowout: definition, 136
  control of ore-carrying solutions: mechanical, 121
    replacement of crystals, 121, 124, 128
  deposition: affected by rock composition, Cartersville, Georgia, 2
    effect of "blanket," 114
    effect of damming of solutions, 85, 116
    fractures not necessary, 120, 121, 123, 128
    in gas phase, 129
    structural control in fissure veins, 65
    structural control necessary? 111
  direction of vein: cause of changes, 65, 82, 92
  disseminated: example, 133
  effect of width of vein: formulas, 127
  environment of ore body: criteria related to ore occurrence: nature, 96
    definition, 96, 102
    empiricism: pitfall, 99, 426, 428
    vein morphology: portraying, 103
  epithermal precious-metal veins: criteria related to bottoming of ore, 140
  fissure veins: in competent rock, 89
    mechanics of fracturing indication of structurally favorable places, 65, 84
    structural control of deposition, 65, 84
    structural control: zigzag, 82, 92, 94
  genesis: United States, 57
  influence of structure on richness of vein, 119
  magnitudes of districts: United States, 9
  mineral paragenesis at Leadville, Colorado, 264
  mineralization in pillow lavas, 130

- Ore deposits: regional pattern, 40, 42
  - roots: cause of decline in value, 138
    - definition, 132, 134
    - empirical methods of determination valuable, 426
  - structural control: Cartersville, Georgia, 279
    - epithermal precious-metal veins, 142
    - in fissure veins, 65, 84
    - is deformation always necessary? 111
  - structure: Continental framework, 9
  - three-dimensional patterns as clusters rising from roots in basement rocks with details controlled by structure of cover rocks, 9
  - width of vein: relation to direction, 65, 84
    - relation to richness, 85
- Ore search: brief bibliography, 146
  - chemical and physical characteristics in limestone that determine aspects as reservoirs for ore and other minerals, 111, 126
  - criteria for determining roots of ore deposit, 111, 132
  - experimental technique in study: example, 127
    - needed, 145
  - structural deformation necessary for migration of mineralizing solutions? 111, 112
  - symposium, Feb. 1938, 111
- Orogenic belts: United States, 47

P

- Philippine Islands: Camarines Norte district: mining companies, 192
  - San Mauricio Mining Co.: mining, milling and geology, 190
- Porcupine gold area: geology: McIntyre mine, 151
- Prettyboy Dam: large-diameter core drill used in exploration, 353
- Privateer mine, B. C.: migration of mineralizing solutions, 117

R

- Rand Fund: Structure of Ore Districts in the Continental Framework, by Paul Billingsley and Augustus Locke, 9
- Ray quadrangle, Arizona: aerial map, 372
- Rocks: failure under stress: bedding planes as loci of weakness, 78
    - brief bibliography, 86, 93, 110
    - control of ore deposition, 104
    - effect of width of opening on mineralization: formulas, 127
    - effect on epithermal precious-metal veins, 142
    - fracture patterns: departures from ideal, 74
      - ideal, 73, 88, 94
    - influence of preexisting structural features in formation of fracture patterns, 65
    - mechanical principles: flow, 66, 70, 87
      - shear, 69, 88, 93
      - stress: definition, 66
- Rocks: igneous: gases in: composition, 231

S

- Sales, R. H.: *Discussion on Ore Search*, 116, 129, 134
- Salt Lake crossroads: regional pattern, 40
- Sampson, E.: *Discussion on Ore Search*, 122
- San Francisco volcanic field, Arizona: aerial map, 390
- San Mauricio Mining Co., Philippine Islands: area and scope of work, 190
  - geology of property, 195, 216
  - history of property, 192
  - labor, 219
  - metallurgical experimental plant, 215
  - milling practice and costs, 213
  - mining methods and costs, 208, 216
  - safety and health, 217, 220
- Ship Rock area, New Mexico: aerial map, 385
- Sienna deposits: deposition controlled by structure and rock composition: Cartersville, Georgia, 276
- Silver City area, New Mexico: aerial map, 378
- Singewald, J. T.: *Discussion on Large-diameter Core Drill for Geologic Exploration*, 353
- Snelgrove, A. K.: *Discussion on Ore Search*, 130
- Stevenson, J. S.: *Discussion on Ore Search*, 117

T

- Tetreault mine, Quebec: principles governing localization of ore, 257
- Teziutlan copper-zinc deposit. *See* Copper-zinc.
- Thoenen, J. R.: *Discussion on: Large-diameter Core Drill for Geologic Exploration*, 351
- Thomson, F. A.: *Discussion on Ore Search*, 136
- Tintic ore district: geology, 16

V

- Vaupell, C. W.: *Mercury Deposits of Huitzuco, Guerrero, Mexico*, 300

W

- Walker-line tear faults, 61, 64
- Wire saw: large-diameter core drill aids in operation, 352
- Wisser, E.: *The Environment of Ore Bodies*, 96
  - *discussion*, 427
  - *Discussions: on Ore Search*, 140
    - *on Structural Control of Ore Deposition in Fissure Veins*, 87
    - *on Structure of Ore Districts in the Continental Framework*, 61
- Witwatersrand: relation of structure to amount of ore, 119
- Wright, L. B.: *Discussion on Ore Search*, 112
- Wynne, V. A.: *Discussion on Use of Aerial Photographs in Geologic Mapping*, 408

Z

- Zinc-pyrite deposits: principles governing localization of ore, 126, 253

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